UCL INSUFFICIENCY

of the ELBOW

IN
OVERHEAD
ATHLETES

HISTORY, WORKUP, AND PATHOANATOMY

RIK J MOLENAARS

Insufficiëntie van het ulnaire collaterale ligament
van de elleboog in bovenhandse sporters
Geschiedenis, benadering en pathoanatomie

ULNAR COLLATERAL LIGAMENT INSUFFICIENCY
OF THE ELBOW IN OVERHEAD ATHLETES
History, workup, and pathoanatomy

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Preface

I have been a fan of sports for as long as I can remember. During childhood, football was my primary (and frankly, only) interest. However, as I went through my studies in physical therapy and medical school, along with the maturation of my brain, my interest in other sports grew. The desire to align my PhD research with a deeper understanding of the United States' unique sports culture led me to MGH's Sports Medicine Center in Boston. Here, I focused my academic pursuits on an injury so intimately related to America's favorite pastime - baseball - that I cannot imagine a more satisfying topic for my thesis.

In collaboration with the Onze Lieve Vrouwe Gasthuis (OLVG, Amsterdam), Amsterdam University Medical Center, Amphia Hospital (Breda), and Erasmus Medical Center (Rotterdam), I delved into the study of ulnar collateral ligament injuries of the elbow in overhead throwing athletes.

I hope this thesis provides a deeper appreciation of the art of throwing (fast) and contributes to our understanding of the pathogenesis and prevention of athletic elbow injuries. I intended to approach these topics from a broad perspective by touching upon contemporary concepts in sports physiotherapy and human movement sciences and exploring how emerging findings resonate with our European perspective on UCL injuries.

With this, I believe this thesis will be of interest to anyone involved in research and care of overhead athletes.

Rik Molenaars

Nijmegen, June 2024

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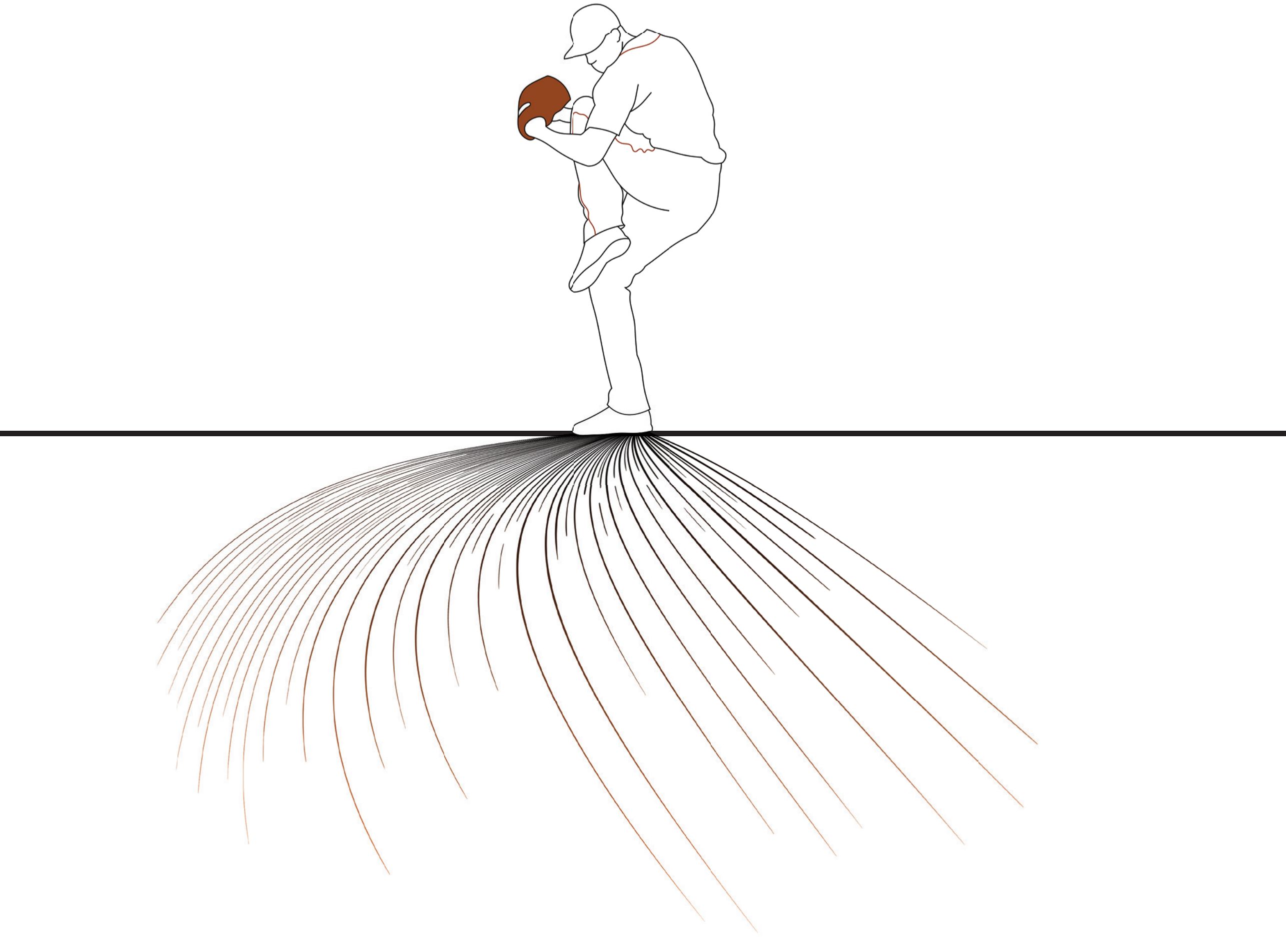
There is something particularly unique in the experience of
viewing the individual athlete. In viewing the individual athlete's
effort limit, the modern spectator feels and thinks
two contradictory emotions simultaneously:
identification and distance.

On the one hand one thinks "that could be me",
but at the same time one understands "that could never be me".

HANS ULRICH "SEPP" GUMBRECHT, author of
In Praise of Athletic Beauty (2006)



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Introduction and thesis outline

ON THE ORIGIN OF THROWING

Two million years ago, approximately four million years after our ancestors started walking on two feet, we shrugged off our ape-like posture by opening up our chest. The orientation of the glenoid cavities, now pointing outwards instead of upwards, dramatically increased our shoulder's elastic energy storage capacity* and allowed the species *Homo erectus* † to throw spears and rocks with high speed and accuracy (figure 1.1).[1] Utilizing this new skill, hominins could hunt down larger prey and expand their diet; archeological evidence suggests that hunting activity intensified around this time. No longer depending on vegetation, desert landscapes could be crossed, and *H erectus* would soon disperse from Africa – thanks, in part, to its unique ability to throw fast and precise.[2] We no longer rely on throwing objects for survival, but the human proclivity to throw and hit overhead persists in many sports.[3]

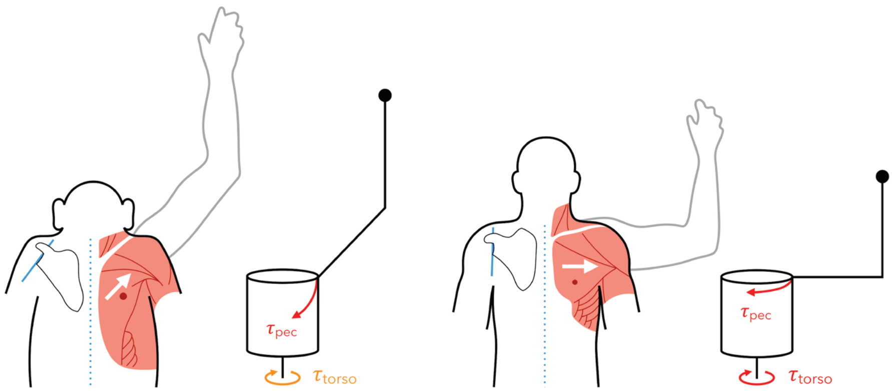

Figure 1.1 The evolution of throwing: chimpanzee versus man. Differences in shoulder orientation (vertebral-glenoid angle, in blue) alter the major line of action of the pectoralis major muscle (white arrows). Tau (τ) vectors showing input torques. Adapted with permission from Roach, *et al*. (*Nature* 2013).

* In 2013, biological anthropologist Neil Roach and colleagues published a paper in *Nature* arguing that the combination of three derived morphological features enables elastic energy storage and release at the shoulder, resulting in our modern-day ability to throw: 1) tall mobile waists, permitting torso rotation; 2) decreased humeral torsion, extending the rotational range of motion at the shoulder externally; and 3) laterally oriented glenohumeral joints. These features evolved in a mosaic fashion, but their combined configuration was first present in *H erectus* (the "upright man").

† Scientists disagree over how *H erectus* and *H sapiens* relate to each other (a central question in the study of human evolution and beyond the scope of this thesis), but most agree that *H erectus* can be called an ancestor of modern humans. Presumably, election for throwing had an important role in the evolution of the genus *Homo*.

THE ART OF THROWING (FAST)

The fastest throwers on earth are baseball pitchers, frequently recording pitches well over 100 miles per hour (160 km/h). The pitching motion follows a set pattern of six phases – windup, stride, arm cocking, acceleration, deceleration, and follow-through – which are fundamental for the sequential buildup and transfer of energy from parts farther from the baseball to parts closer to the baseball, maximally utilizing the kinetic chain (figure 1.2).[4,5]

Pitching is about stride foot landing, hip-to-shoulder separation, torsal twist, and arm cocking, followed by 42 to 58 milliseconds (less than one-fifth of the blink of an eye) in which the elastic energy is rushed into the shoulder, loading muscles, tendons, and ligaments until the shoulder cannot rotate further. Subsequently, the elastic energy is turned into kinetic energy. By transferring this energy down the chain, the arm rotates internally with great velocities of up to 8,000 degrees per second. Along with the extension of the elbow, the arm is propelled forward. As the energy travels down the arm and through the baseball, shoulder muscles contract to help the arm decelerate, and the remaining energy dissipates during follow-through.

Imperative for our understanding of the throwing motion is that it involves the complete kinetic chain, from toe to fingertip, with every segment of the chain contributing to the buildup and transfer of energy from the lower legs to the throwing hand. There is emerging evidence for the pivotal role of the legs and trunk in generating velocity, while the arm sequentially coordinates and fine-tunes the delivery.[6] Regardless of the contributions of various body parts to the functioning of the kinetic chain, when repeatedly throwing as fast as humanly possible, its weakest link may eventually break.

THE WEAKEST LINK

The throwing motion has interested scientists for decades. Advanced biomotion analysis techniques have allowed scientists to study the biomechanics of this extremely fast motion in baseball pitchers in great detail and have provided substantial insight into the kinetic chain of throwing and the forces that act upon the thrower's shoulder and elbow.

In 1995, Fleisig and colleagues identified two 'critical instants' for injury during the pitching motion (figure 1.3).[7] The first instant occurs during late cocking, just before maximum external rotation of the shoulder, with the elbow flexed approximately 95 degrees, when varus torque (also known as moment, or moment of force: the tendency of a force to cause the rotational motion of a body)

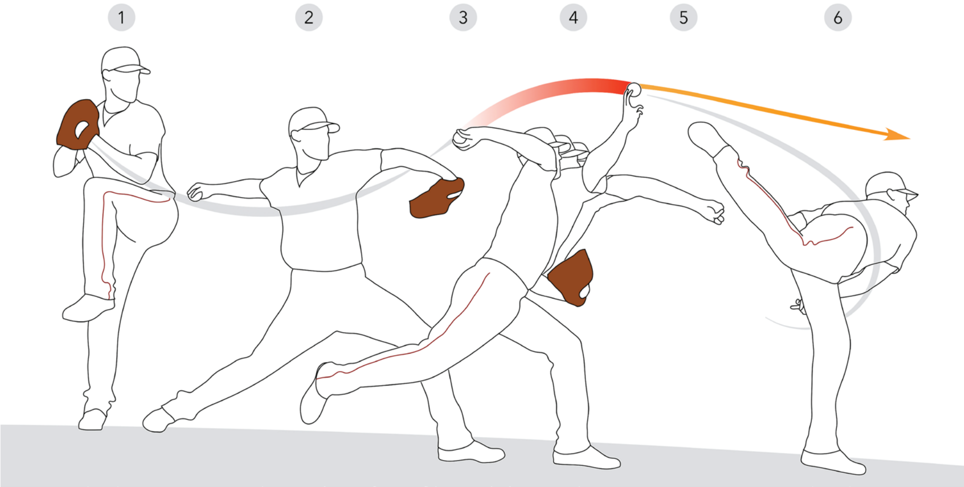

Figure 1.2 Six phases of throwing: The primary goal of the first three phases – windup (1), stride (2), and arm cocking (3) – is to generate elastic energy by stretching ligaments and tendons throughout the body. Subsequently, this elastic (potential) energy is turned into kinetic energy, propelling the arm forward in a movement that combines internal rotation of the shoulder and extension of the elbow. Ending with the release of the baseball, this acceleration phase (4) takes 42 to 58 milliseconds to complete. After ball release, contraction of arm and shoulder muscles, forearm pronation, and movement of large body parts (i.e., trunk, legs) help dissipate the remaining energy during deceleration (5) and follow-through (6).

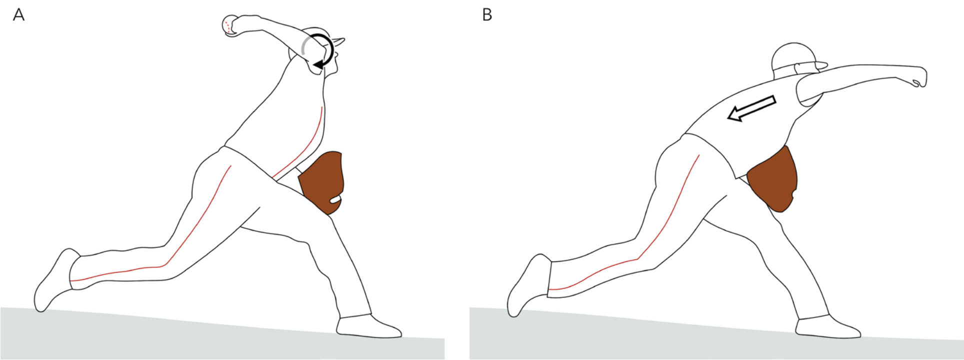

Figure 1.3 Two 'critical instants' during the throwing motion: A) the first critical instant occurs shortly before maximum external rotation of the shoulder, with the elbow flexed approximately 95°, when the external valgus and internal varus torque of the elbow reach their highest levels, resulting in the maximal tensile forces absorbed by the ulnar collateral ligament; B) the second critical instant occurs shortly after ball release, during arm deceleration, with the elbow flexed approximately 25° when the maximum compressive force is generated at the shoulder, reflecting the pulling forces on the rotator cuff and joint capsule resisting glenohumeral distraction.

of the elbow reaches its highest level. This first instant is, therefore, associated with throwing-related injuries to the elbow. The second instant occurs shortly after ball release during arm deceleration, when a maximum compressive force is generated at the shoulder. The rotator cuff muscles and shoulder joint capsule resist the glenohumeral distraction force when the thrower's arm is propelled outwards, which explains the susceptibility of baseball pitchers to shoulder injury.

These latter types of injuries (i.e., of the shoulder, such as biceps brachii tendinopathy, rotator cuff tears, and labral lesions) used to be the bane of baseball, causing nearly 7,000 disabled list days ‡ as recently as 2008 in Major League Baseball pitchers.[8] This number dropped to less than 3,000 disabled list days by 2014, attributed to advancements in exercise programs for shoulder muscle strengthening.[2] With the shoulder now better equipped to withstand internal and external forces generated by throwing, the elbow is left to fend for itself.

ELBOW INJURIES IN BASEBALL

The elbow joint derives its stability from osseous, ligamentous, and muscular structures (box 1.1). The anterior bundle of the medial ulnar collateral ligament complex – often referred to as "medial collateral ligament (MCL)" in Europe or simply "UCL" in the United States – spans the medial elbow and connects the medial epicondyle of the humerus and the sublime tubercle of the ulna. This small ligament, measuring approximately 3 centimeters in length and 6 millimeters in width, provides primary resistance to the valgus torque generated at the elbow with powerful overhead throwing.[9-11]

Biomechanical studies applying inverse dynamic analyses have estimated that the UCL is loaded at its maximum capacity with each baseball pitch.[12] The UCL generates 54% of the varus torque to resist valgus motion when the elbow is in 90 degrees of flexion.[13] In vitro studies using adult cadavers have observed failure of the anterior bundle with valgus torques of approximately 30 Newton-meter (Nm)[14,15] and studies using bone-ligament-bone complexes found maximal strength of the anterior bundle of the UCL of 260 to 293 Newton.[16,17] Assuming similar in vivo torques during pitching, Fleisig and colleagues (1996) found the UCL to provide a mean varus torque of 34.6 Nm in twenty-six baseball pitchers, which is, quote, *"near its maximum capacity based on preliminary cadaveric testing that indicates a maximum varus torque of 32.1 ± 9.6 Nm before failure of the UCL"*.[18]

‡ In Major League Baseball, the 'disabled list' or 'injury list' (official term since 2020 after disability advocates requested a name change) is a method for teams to remove injured players from the roster to add healthy players. It provides an invaluable public source of data on baseball injuries and their impact on game participation that is commonly used in *sabermetrics*; the application of statistical analysis to baseball records.

With powerful throwing depending on this small ligament, baseball pitchers are prone to UCL injury. Insufficiency of the UCL encompasses micro-traumatic lengthening or tearing of the anterior bundle of the MCL complex, which may lead to a myriad of symptoms, including medial elbow pain, medial elbow instability, and decreased throwing velocity and command (i.e., precision of throwing). In addition, UCL insufficiency has been associated with various other throwing-related elbow pathologies, such as radio-capitellar osteochondritis dissecans, posteromedial osteophytes, and ulnar neuropathy (valgus-extension overload syndrome; figure 1.4), as well as apophyseal injuries or stress fractures of the olecranon and medial epicondyle.[19,20] In the second chapter of this thesis, which serves as an extension to this introduction, the implications of the vulnerability of baseball pitchers to UCL injury and the historical perspective on its main treatment are discussed in more depth.

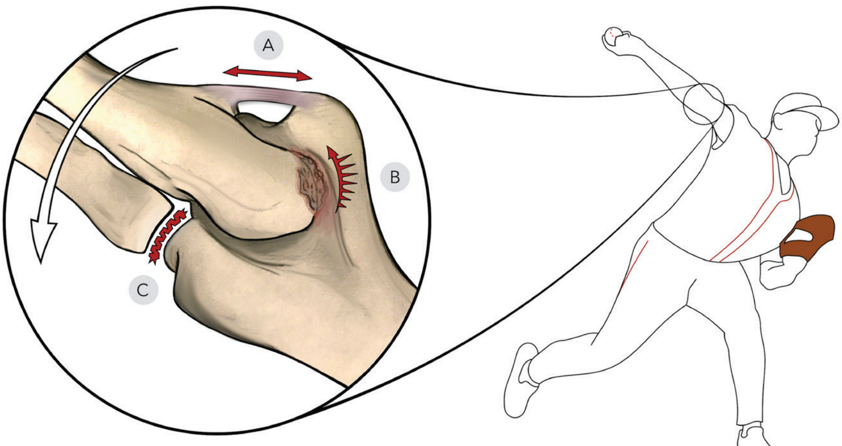

Figure 1.4 Valgus extension overload syndrome: the capacity of the ligamentous, muscular, and osseous structures to withstand pulling, compression, and shear forces on the medial, lateral, and posterior side of the elbow is challenged by the high valgus and extension loads generated during powerful overhead throwing and may lead to ulnar collateral ligament injury (A), posteromedial chondromalacia and osteophytes (B), radio-capitellar osteochondritis dissecans (C), and traction ulnar neuropathy.

BOX 1.1 ELBOW ANATOMY

The elbow joint consists of the humeroulnar (medial), humeroradial (lateral), and proximal radioulnar articulation. The first two articulations allow the ginglymoid motion in flexion and extension, and the latter articulation allows the trochoid motion in pronation and supination, creating a trochleo-ginglymoid joint that is one of the most congruous and stable joints of the human body.[21] The elbow's carrying angle is measured in full extension and defined by the angle between the long axis of the humerus and the ulna, averaging 11-14 degrees in males and 13-16 degrees in females.[11] The joint capsule shows lateral and medial thickening, which form the lateral and medial collateral ligament complex, respectively.[22] These complexes are the primary static stabilizers of the elbow.

Ligaments – The lateral collateral ligament complex (LCL) consists of the annular ligament, radial collateral ligament, lateral ulnar collateral ligament, and accessory collateral ligament (with considerable variability of these components among individuals).[23] The LCL complex originates along the inferior surface of the lateral epicondyle and is taut throughout elbow range of motion.[11] The lateral ulnar collateral ligament is the primary restraint to varus stress, and insufficiency of this ligament – usually traumatic or iatrogenic – leads to posterolateral rotatory instability of the elbow.

The medial collateral ligament complex (MCL) comprises the anterior, posterior, and transverse bundles. The anterior bundle or anterior oblique ligament is the most significant component of the MCL and the primary restraint to valgus stress (figure 1.5).[11,17,24,25] The proximal attachment of the anterior bundle is at the antero-inferior tip of the medial epicondyle. The distal attachment of the anterior bundle is at the ulnar sublime tubercle, with some fibers inserted further distally on the proximal and medial ulna.[26,27] The anterior bundle can be subdivided into an anterior and posterior band (some authors have included a third deep middle band), which are not isometric in function.[11,28] Due to the positioning of the origin of the anterior bundle (i.e., slightly posterior to the axis of rotation of the elbow), the anterior band is taut in extension, and the posterior band is taut at intermediate flexion positions. The posterior bundle or posterior oblique ligament is a fan-shaped ligament attached proximally to the postero-inferior aspect of the medial epicondyle and attached distally to the medial

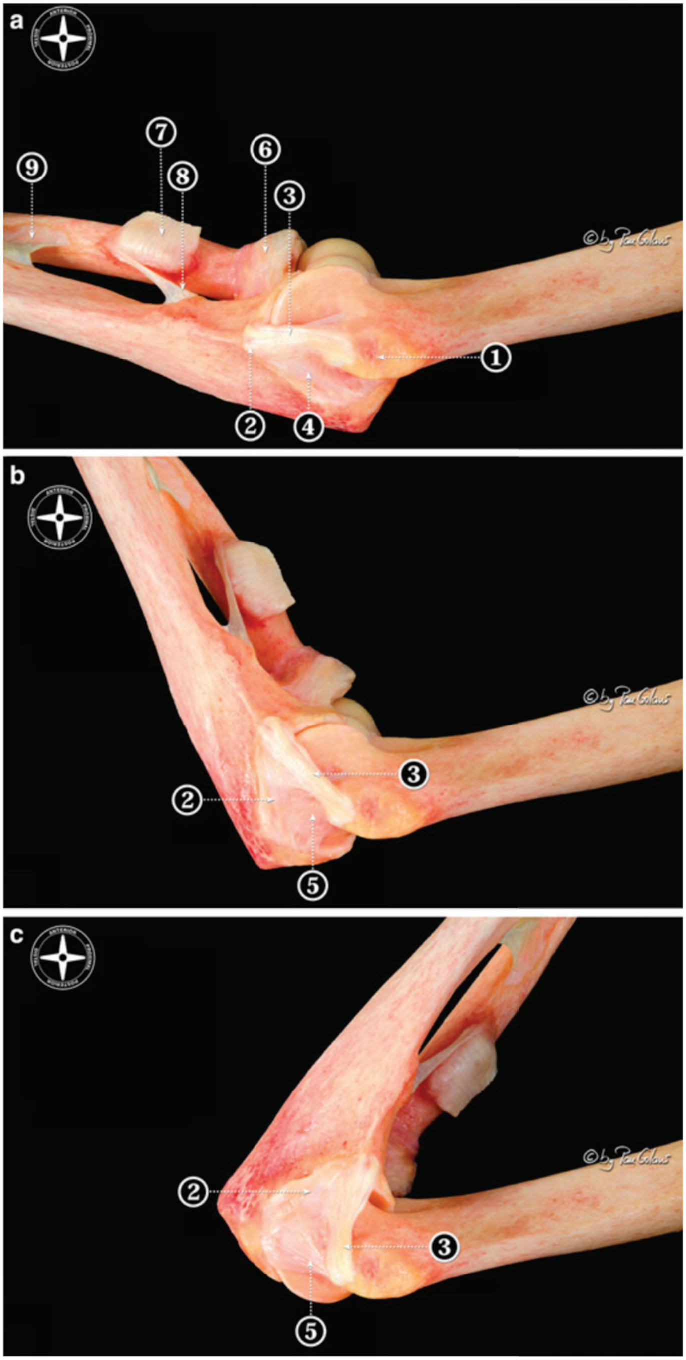

Figure 1.5
Medial osteoarticular view of the elbow showing the morphology of the MCL complex during elbow range of motion:
a) full extension
b) 90° of flexion
c) full flexion

1. medial epicondyle
2. sublime tubercle
3. anterior bundle
4. transverse bundle
5. posterior bundle
6. annular ligament
7. biceps brachii tendon
8. oblique cord
9. interosseous membrane

Reused with permission from Malagelada, *et al*. (Springer 2014).

olecranon. The transverse bundle spans the insertion of the anterior and posterior bundle and covers a depression of the medial ulna below the ulnar notch. The transverse bundle is intimately attached to the joint capsule and does not significantly contribute to elbow stability.[23]

Musculature – The musculature of the elbow can be classified into anterior and posterior muscle groups mainly functioning as elbow flexors (biceps brachii and brachialis muscle) and elbow extensors (triceps brachii muscle), respectively, and medial and lateral muscle groups mainly functioning as wrist flexor-pronators and extensor-supinators. The flexor-pronator muscle mass originates from the medial epicondyle and fan out laterally as the pronator teres, flexor carpi radialis, palmaris longus, and flexor carpi ulnaris. Of these muscles, the flexor carpi ulnaris lies directly over the MCL complex and contributes significantly to valgus stability. The flexor digitorum superficialis provides similar dynamic stability in greater degrees of elbow extension.[29,30]

Nerves – The musculocutaneous, radial, median, and ulnar nerves cross the elbow, of which the ulnar nerve is the most relevant in the overhead athletic population. The ulnar nerve enters the cubital tunnel (a fibro-osseous ring formed by a fascial sheath between the medial epicondyle and the olecranon) posterior to the medial epicondyle. It continues to the anterior compartment of the forearm between the two heads of the flexor carpi ulnaris muscle.[11,31] The ulnar nerve is prone to compression by thickening of the cubital tunnel, and ulnar nerve irritation or neuropathy is frequently observed in overhead athletes.

See Malagelada *et al*. (2014) for an extensive overview of the elbow's anatomy.[11]

UCL INJURY: RELEVANT TO BASEBALL ALONE?

UCL injuries are a significant problem in throwing-dominant cultures, such as the United States and Japan. As a result, most scientific data on throwing-related elbow injuries, including the studies presented in the current thesis, originate from the continents of North America and Asia and mainly focus on baseball pitchers. In contrast, the first studies on UCL injuries based on European data were only published around the turn of the 21st century.[32,33] Given the relative lack of studies on UCL injury in non-baseball (European) athletes, the body of knowledge on pitching and associated elbow injuries offers an essential point of departure to advance our understanding of throwing-related elbow injuries in other overhead sports.

Despite considerable variation in intention of movement (whether it is throwing or hitting an object), overhead athletic activities share striking similarities. These similarities can be obscured by various amounts of trunk lateral flexion, which primarily determines the spatial orientation of the upper extremity and significantly influences the outer appearance of athletes in action (figure 1.6).[34]

During the first phases (windup, shoulder cocking, acceleration) of throwing or hitting (e.g., in tennis serving and volleyball spiking), the shoulder is brought into approximately 90 degrees of abduction and external rotation, the elbow is flexed, and the forearm is supinated (figure 1.7). Conversely, the deceleration and follow-through phases are characterized by shoulder adduction and internal rotation, elbow extension, and forearm pronation (figure 1.8).[35] These so-called generic movement patterns result from self-organization of the human body. The concept of self-organization will be elaborated on in the discussion of this thesis and has importance in contemporary training theories.

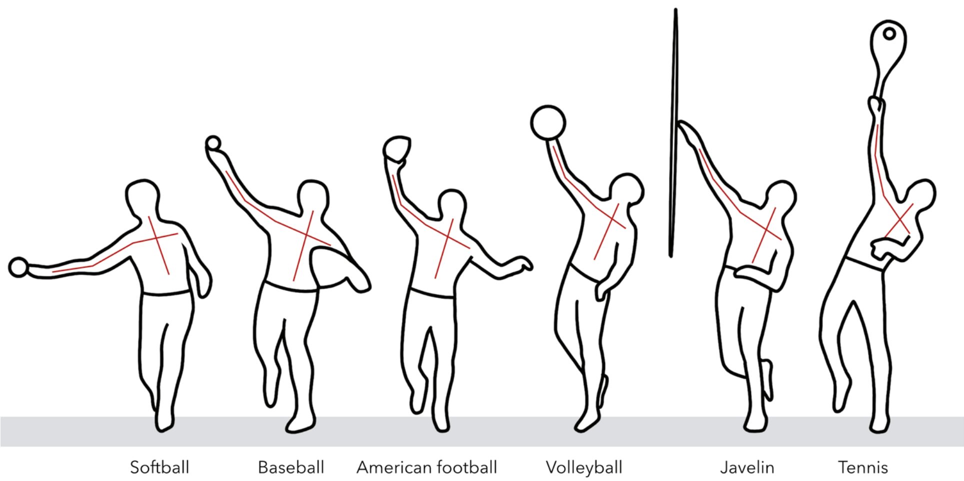

Figure 1.6 Release positions in a variety of unilateral throwing and striking skills. Lateral strunk flexion toward or away from the throwing arm, rather than shoulder joint action, determines the spatial orientation of the arm at object release. Reused with permission from Atwater (*Wolters Kluwer*, 1979).

Figure 1.7 Generic movement patterns in overhead athletics (windup/late-cocking/early acceleration): shoulder abduction-external rotation, elbow flexion, and forearm supination.

Figure 1.8 Generic movement patterns in overhead athletics (deceleration/follow-through): shoulder adduction-internal rotation, elbow extension, and forearm pronation.

Given the marked similarities of overhead athletic activities, the implications of research findings on UCL injury in baseball players may extend beyond baseball players to other overhead athletes. The final chapter of this thesis will touch upon this topic in more detail, discussing how we can utilize insights on baseball-related elbow injuries as a proxy for UCL injury in other sports. As such, this thesis may interest researchers and clinicians involved in the study and care of a range of overhead athletes.

THESIS OUTLINE

The research presented in this thesis was performed in collaboration between Massachusetts General Hospital's Sports Medicine Center (Harvard Medical School, Boston, USA), Onze Lieve Vrouwe Gasthuis (OLVG, Amsterdam), Amsterdam University Medical Center, Amphia Hospital (Breda), and Erasmus Medical Center (Rotterdam). This thesis is a clinically-oriented exploration of athletic overuse injury to the UCL, in order to advance our scientific foundation from more expert-opinionated to evidence-based practice.

The US has observed a striking increase in surgical procedures performed for UCL injuries in youth and professional baseball pitchers over the past decades. This trend needs to be better understood. The implications of the near maximum loading of the UCL in baseball pitchers are outlined in greater detail in **Part I** of this thesis, drawing out the history of UCL injury and introducing the 'epidemic' of reconstructive surgery performed in baseball pitchers to date (**Chapter 2**). Renowned elbow specialists Dr. James R. Andrews and Prof. dr. Roger van Riet provide their expert opinions on the UCL issue in Chapter 2's **Supplemental material**.

Part II of this thesis explores various aspects of the clinical workup of UCL injuries to establish an optimal and efficient approach to throwing athletes with medial elbow pain. The study presented in **Chapter 3** targets the clinical value of the athlete feeling or hearing a "pop" at the time of injury; does this salient anamnestic finding suggest significant UCL injury in throwing athletes? In **Chapter 4**, outcomes of clinical stress radiographs and their relationship to UCL injury severity are analyzed to determine if assessment of medial elbow joint opening is useful in the clinical workup of throwing athletes presenting with medial elbow pain.

Part III of this thesis focuses on the pathoanatomy of UCL injury and reconstructive surgery of the elbow and forearm. A comprehensive understanding of the anatomy and pathoanatomy of injury is fundamental for optimal results in surgical procedures. In search for an improved anatomical description of injury based on clinical data and aiming to enhance our understanding of UCL injuries, **Chapter 5** provides a descriptive analysis of injury patterns of the anterior bundle of the MCL complex in a sizeable single-surgeon cohort undergoing UCL reconstruction. Next, **Chapter 6** reviews the use of allografts as an alternative to autografts in elbow and forearm reconstructive surgery: Is there a role for allografts in UCL reconstruction procedures?

The findings of the studies comprising this thesis are discussed in the context of the overall literature in the final chapter of this thesis (**Chapter** 7). This chapter outlines the clinical approach to patients with UCL injury. It assesses whether, and if so, how, current findings on baseball-related UCL injury may apply to other overhead athletes. Finally, critical questions on throwing-related elbow injury prevention are discussed, and avenues for future research are proposed.

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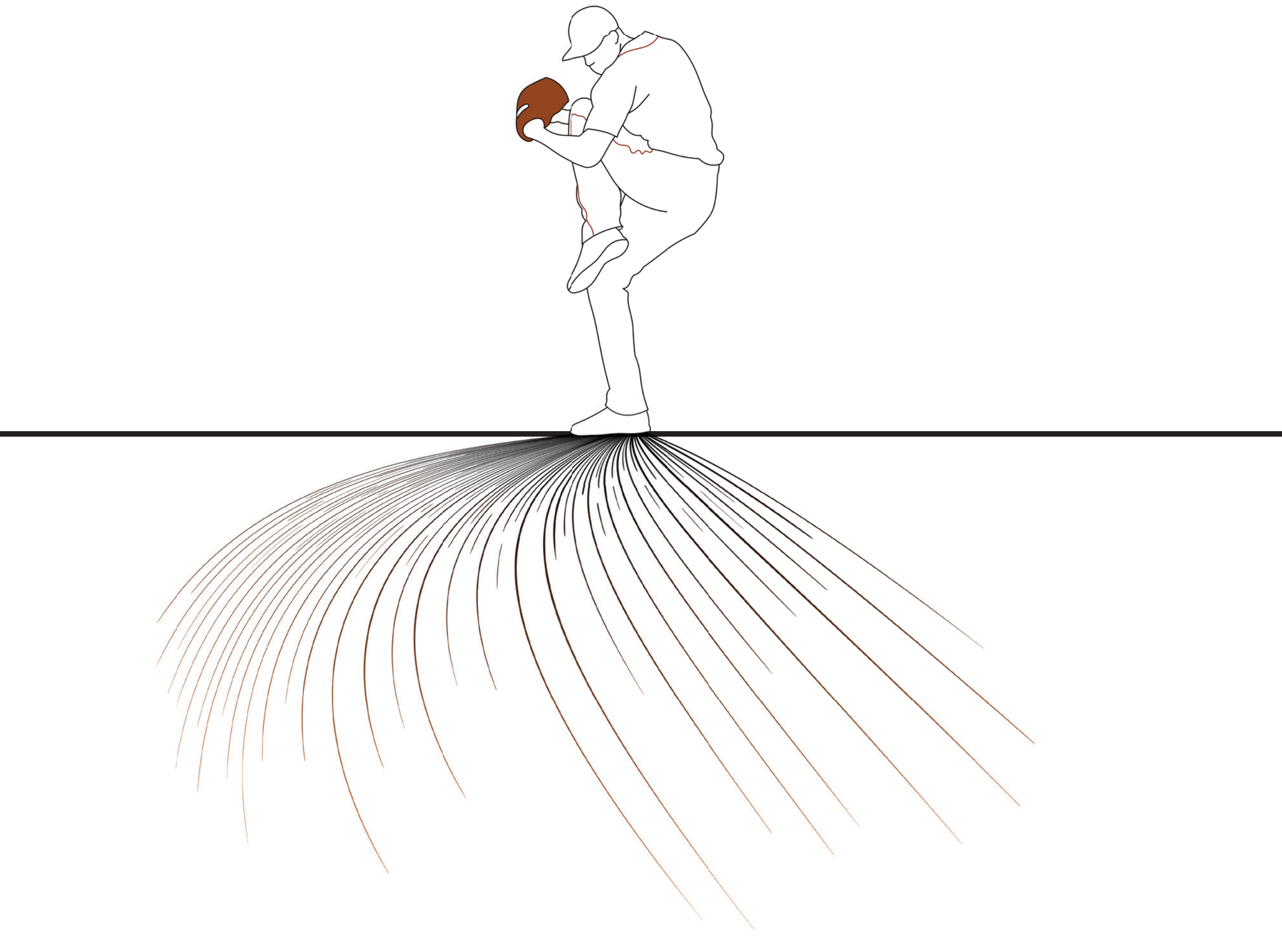
PART I

A HISTORY OF ULNAR COLLATERAL LIGAMENT INJURY



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Review of Jobe *et al.* (1986) on reconstruction of the ulnar collateral ligament in athletes

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ABSTRACT

This classic examines the landmark publication 'Reconstruction of the Ulnar Collateral Ligament in Athletes' by Jobe *et al.*, published in 1986. Dr. Frank W. Jobe was the first to perform and describe a standard technique for ulnar collateral ligament (UCL) reconstruction with the use of a figure-of-eight configuration and submuscular ulnar nerve transposition to treat throwing athletes with UCL insufficiency. Before Jobe's pioneering work, the initial operative approach to patients with UCL tears involved repair of the native ligament. Despite this treatment, injuries of the UCL were considered career-ending in those days.

The original article describes the surgical technique for UCL reconstruction and the postoperative rehabilitation and outcomes in 16 throwing athletes, including Major League Baseball pitcher Tommy John (Los Angeles Dodgers). Jobe *et al.* reported good results, with 10 of the 16 patients returning to their previous level of participation in sports, one patient returning to a lower level of participation and five patients retiring from professional athletics due to reasons not related to the operation. However, a high incidence of ulnar nerve complications was reported, requiring secondary surgery in two patients.

In the decades following the original publication, modifications of the Jobe technique, involving different graft choices, tunnel positions, and graft configurations and fixation methods have resulted in improved clinical results. Originally presented as a treatment option for elite athletes only, UCL reconstruction has gained public interest as incidence rates of 'Tommy John surgery' have reached epidemic proportions, especially in high school-aged baseball pitchers in the USA.

Introduction

Rationale for selecting this article

This classic work by Jobe *et al.*, published in 1986, provided a career-saving surgical technique to treat ulnar collateral ligament (UCL) tears in throwing athletes.[1] The index surgery was performed on September 25, 1974 on baseball pitcher Tommy John of the Los Angeles Dodgers. The publication describing this case among fifteen others was chosen for this 'Classic' because of the epidemic levels of overhead throwing athletes undergoing UCL reconstruction today.[2-7]

Injuries to the UCL typically occur in the overhead throwing population, especially baseball pitchers and javelin throwers, but can also be found in other athletes, including gymnasts, quarterbacks, tennis players, and wrestlers.[8] The UCL is composed of three bundles, of which the anterior bundle is the main soft tissue restraint to valgus instability at 20 tot 120 degrees of elbow flexion (figure 2.1).[9-13] UCL injuries in overhead athletes are considered overuse injuries resulting from repetitive valgus stress during the acceleration phase of the throwing motion.[14] The medial elbow has to withstand approximately 60 Nm during an average baseball pitch. Although surrounding muscles help absorb the forces on the medial elbow, the UCL approaches its maximum stress during every pitch.[15,16] Disruption of the UCL can lead to medial elbow pain and loss of throwing velocity, endurance and control, and may be accompanied by ulnar nerve symptoms and flexor-pronator tendinopathy. Furthermore, insufficiency

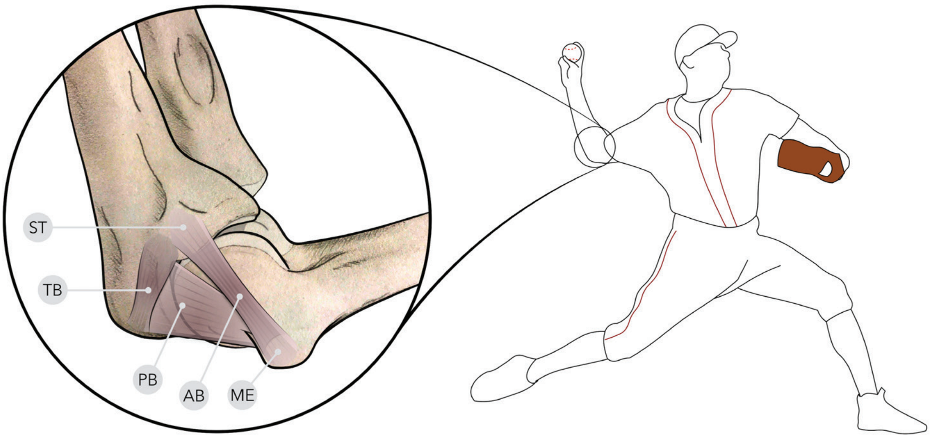

Figure 2.1 Anatomy of the medial collateral ligament complex in the pitcher's elbow. *ST*, sublime tubercle; *TB*, transverse bundle; *PB*, posterior bundle; *AB*, anterior bundle; *ME*, medial epicondyle. The orientation of the depicted bones is in accordance with the throwing figure on the right.

of the UCL has been suggested to be the underlying cause of a variety of other elbow complaints, including valgus extension overload - a cascade of symptoms with osteochondritis dissecans at the radial side, osteophytes and chondromalacia in the posteromedial compartment, ulnar nerve symptoms, and even risk of proximal stress fractures of the ulna.[17]

A recent epidemiological study by Ciccotti *et al.* indicated that elbow injuries are the fourth most prevalent type of injury in the US professional baseball population (7.8% in Major League Baseball and 9.8% in Minor League Baseball), accounting for the highest number of days missed of all musculoskeletal injuries.[18] In this population, 39 to 53% of elbow ligament injuries require surgery, predominantly in pitchers and primarily involving the UCL. Epidemiological studies have shown that the number of UCL reconstructions has been rising steadily.[6] Disturbingly, there is a marked increase in the number of UCL reconstructions performed in amateur and adolescent athletes in the last decade.[3,6,7,19]

Consideration

Historic perspective

The first study on isolated UCL tears was published in 1945 and described UCL injuries in European javelin throwers.[20] Although several reconstructive procedures had long been successfully used in ligaments of other joints, such as the knee and ankle, there was no such procedure for reconstruction of a torn ligament in the elbow. Prior to the Jobe publication, UCL injuries were treated either conservatively or with direct suturing of the native ligament.[21,22] This 'UCL repair' was supported by Barnes and Tullos, who reported in 1978 that throwing athletes had better clinical outcomes after UCL repair than after non-operative treatment.[23] Nevertheless, at that time, UCL tears were typically career-ending for athletes.[24] Unsurprisingly, the utilization of a tendon graft to reconstruct the insufficient UCL by Jobe *et al.* resulting in the return to professional baseball of Major League pitchers gained significant attention in the public and orthopaedic sports community.[1]

Scientific and societal impact

Evolution of Tommy John surgery

Jobe's reconstruction technique or 'Tommy John surgery' defined a new approach towards the treatment of UCL tears. Although the initial results were already promising, with return to sport in 63 to 68% of patients, the surgical technique has been optimized over the past 25 years, improving outcomes and minimizing associated complications.[1,25] An important advancement in the surgical technique was the introduction of the muscle-splitting approach to achieve visualization of the UCL in 1996 by Smith *et al.*, eliminating the transsection and elevation of the common flexor origin used in the original Jobe technique.[26] Furthermore, this new approach no longer required a submuscular ulnar nerve transposition. Seventy-seven out of 83 athletes (93%) reported excellent outcomes after performing a muscle-splitting approach, with transient ulnar neuropathy in only four patients (5%).[27]

Various subsequent alterations and modifications primarily addressed bone tunnel positioning, graft configuration and fixation, and handling of the ulnar nerve, including the Jobe modification,[27] American Sports Medicine Institute modification,[7,28,29] the suture-anchor method or hybrid technique, the interference screw or DANE TJ (David Altcheck-Neal ElAttrache Tommy John) technique,[32-34] and the docking technique (table I).[35-40] In turn, there are numerous modifications of the docking technique, mainly focusing on the preparation of the autograft (e.g., triple-strand, four-strand).[39] Many excellent reviews have been published describing the evolution and outcomes of surgical techniques for UCL reconstruction.[10,12,41-44] Vitale and Ahmad pooled data of clinical series on UCL reconstructions and found that the muscle-splitting approach improved the return to sport from 70% to 87% and reduced ulnar neuropathy from 20% to 6% compared with the flexor-pronator detachment method.[45] Furthermore, they found that the (modified) docking technique improved outcomes from 76% to 90-95% compared with the original figure-of-eight graft configuration.

Choices of graft include the tendon of the palmaris longus, gracilis, semitendinosus, toe extensor, plantaris, and extensor carpi radialis longus muscle, the triceps fascia, and the Achilles tendon. There have been an number of studies on graft choice and graft site mobidity in UCL reconstruction. Currently, there is no evidence for the favourability of one autograft type over another.[46-49]

Table I. Key aspects of modifications of the original Jobe technique for UCL reconstruction.

ASMI modification (1995)	Posterior approach between two heads of flexor carpi ulnaris; elevation of the flexor-pronator mass; subcutaneous ulnar nerve transposition.
Hybrid technique (1998)	Flexor-pronator muscle splitting; humeral and ulnar suture anchors; subcutaneous ulnar nerve transposition.
Jobe modification (2001)	Flexor-pronator muscle splitting; figure-of-eight graft configuration; no ulnar nerve transposition.
Docking technique (2002)	Flexor-pronator muscle splitting; triangular graft configuration with a Y-shaped humeral tunnel; subcutaneous ulnar nerve transposition.
DANE TJ technique (2006)	Flexor-pronator muscle splitting; humeral docking and ulnar interference screw fixation; subcutaneous ulnar nerve transposition.

ASMI, American Sports Medicine Institute; *DANE TJ*, David Altchek-Neal ElAttrache Tommy John; *UCL*, ulnar collateral ligament

Hagemeijer *et al.* found that the palmaris longus tendon is the most frequently used graft in elbow ligament reconstruction procedures (58%).[47] However, the use of this tendon is not an option in all patients as the palmaris longus is absent in one-sixth of the world population, with a wide variation among different ethnic groups.[50]

To date, the docking technique and modified Jobe using a palmaris longus autograft are the most commonly performed surgical procedures for UCL reconstruction with high success rates (figure 2.2).[44,51,52] Despite all innovations, Tommy John surgery is still season-ending and requires 12 to 18 months of rehabilitation.

Rising incidence in UCL reconstructions

In accordance with the increase in the number of participants in overhead throwing sports, there has been an increase in the incidence of upper extremity injuries in the past decades.[53] To date, 25% of Major League pitchers and 15% of Minor League pitchers have had Tommy John surgery at some point in their career.[5] In a recent comprehensive epidemiological study, Ciccotti *et al.* found that 33 to 43% of elbow injuries in US professional baseball require surgery, with UCL reconstruction being the most frequently performed procedure.[18] Although no increase in the frequently of elbow injuries was observed over recent

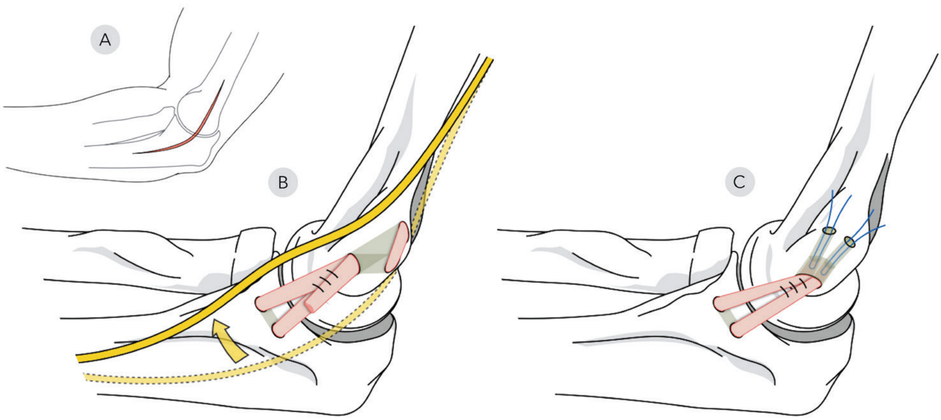

Figure 2.2 The original Jobe technique (1986): A) medial elbow incision; B) ulnar and humeral bone tunnels with figure-of-eight graft configuration and anterior transfer of the ulnar nerve; C) the docking technique: stitched graft ends are tied securely over the humeral bone bridge.

seasons in this population, Erickson *et al.* reported a significant increase in UCL reconstructions performed from 2000 to 2012.[5,18,54,55]

Disturbingly, there has been a notable and disproportionate increase in the number of reconstructive surgical procedures performed in elbows of young overhead throwing athletes.[2-6,56] The overall number of UCL reconstructions performed between 2003 and 2014 has increased by 343%.[6] In 2014 alone, more pitchers had undergone UCL reconstruction than in the entirety of the 1990s, and the rate of adolescent players undergoing surgery has been rising from none in the early 1990s to more than 40% in recent years (figure 2.3). The incidence of elbow pain in baseball players ranges from 20 to 30% in players aged 8 to 12 years, to 45% in 13 and 14 year-olds, and over 50% in high school, collegiate, and professional athletes.[57] Currently, 57% of Tommy John surgeries are performed on athletes aged 15 to 19 years.[4]

The rise in incidence of UCL reconstructions has become a hot topic in recent years, especially in the United States. As the amount of competitive pitching and pitching when fatigued are strong risk factors associated with UCL injury, it is likely that pitching too hard, too fast, too much, and too soon are major contributors to this phenomenon.[58-62] The influence of the widespread use of radar guns by talent scouts and the prospect of college scholarships (that provide an opportunity to secure a higher socioeconomic status in the US

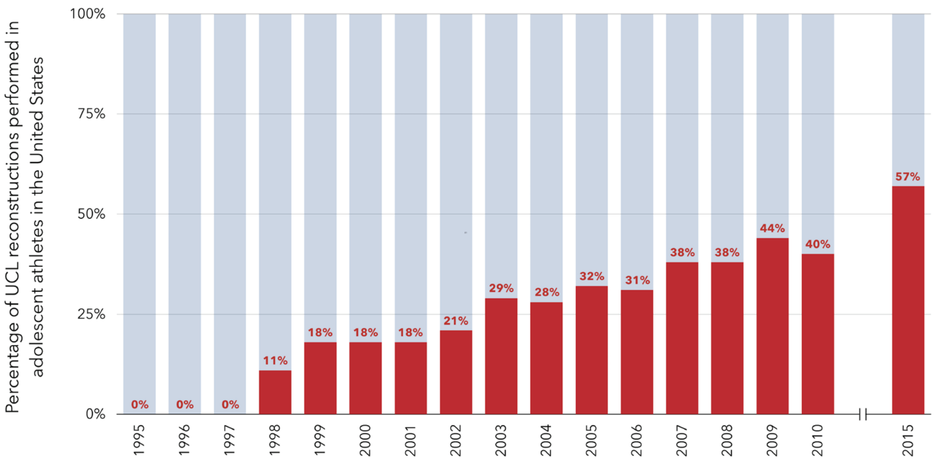

Figure 2.3 The rising incidence of ulnar collateral ligament reconstructions performed in young overhead throwing athletes from 1995 to 2015, based on publicly available data of the American Sports Medicine Institute and Erickson *et al.* (2015).

educational system) may be underexposed in current literature, pushing young athletes to their limits.

Determining the age and competitive level that define early sport specialization is challenging and conclusive evidence linking early sport specialization to injury is lacking. Nevertheless, it has been stated that the increase in year-round baseball has led to the 'skyrocketing' rate of UCL injuries in young baseball players.[63,64] This idea initiated the institution of age-related pitch count recommendations by USA Baseball in 2008. It is difficult to determine whether these recommendations are inadequate or that there is a lack of compliance, but UCL injury rates have nonetheless continued their steady increase.[58] A cross-sectional study of 754 youth and adolescent pitchers (9-18 years) showed that 45% had no pitch count in place and more than 13% pitched more than the recommended 8 months per year, suggesting the possibility of a lack of compliance. Further research is needed to determine the long-term effects of early single sport specialization and define ranges of 'healthy' single sport specialization in different types of sport.

A third factor that has been suggested for the disproportionate rise in UCL reconstructions is the occurrence of 'false' public perceptions of Tommy John surgery among athletes, coaches, parents, and the media. Ahmad *et al.* noticed the increasing number of uninjured young throwers who presented at their clinic for medical evaluation, seeking UCL reconstructive surgery, and hypothesized that the general public has misguided perceptions regarding the causes of UCL injury and the indications, operative technique, risks, benefits, and required rehabilitation.[65] They found that over 25% of baseball coaches, players, and parents do not believe that pitch count is a risk factor for elbow injury. In the same study, and arguably most importantly, 30% of baseball coaches, 37% of parents, 51% of high school athletes, and 26% of collegiate athletes believed that UCL reconstruction in athletes without UCL injury would improve performance (figure 2.4). In 2015, Conte *et al.* performed a similar study to examine the media's perception regarding UCL injury treatment.[66] One in four respondents believed the primary indication for UCL reconstruction was performance enhancement and 20% felt that throwing velocity increased compared with pre-surgery velocities. No studies have truly demonstrated performance above pre-injury level after Tommy John surgery, but did report the ability to return to the same level of performance after surgery.[45,67,68]

Current evidence as related to the original article

Outcomes and revision surgery

Reported success rates of UCL reconstruction, defined as a patient being able to return to his or her previous level of sport, consistently range between 80%

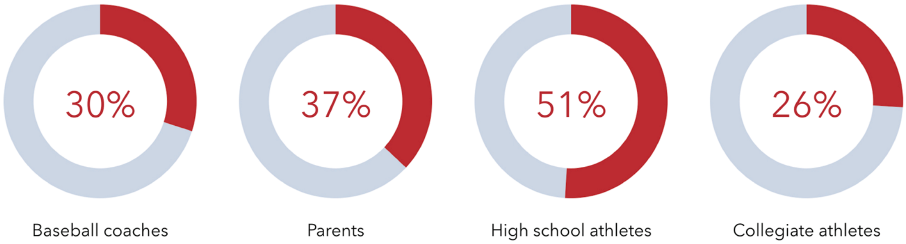

Figure 2.4 Belief in performance-enhancing ability of UCL reconstruction among baseball coaches, parents, and high school and collegiate athletes.

and 90%.[7,25,35-37,45,69] In a 10 year follow-up study on long term outcomes in competitive baseball players, Osbahr *et al.* indicated a return to throwing in 4.2 months and return to game competition by 11.6 months.[69] Furthermore, they found that most patients are satisfied, with few reports of persistent elbow pain or limitation of elbow function during activities of daily living. Overall complication rates range from 10% to 15%, with ulnar nerve paresthesias averaging at 6%.[45] Systematic reviews have suggested that the docking technique may have the lowest complication rate and a higher rate of return to play relative to other techniques, but these differences are not statistically significant.[70]

Although excellent results can be expected in most patients who undergo primary UCL reconstruction, less is known about revision reconstruction of the UCL. Incidence of revision surgery has been found to range between 13% and 15%.[71,72] Dines *et al.* provided a clinical report on the postoperative outcome of revision UCL reconstruction in a series of fifteen baseball players in 2008.[73] Only five patients (33%) were able to return to their previous level of competition for at least one year. The complication rate was high (40%), with two of the complications being major (re-tear of the revision graft and loss of elbow range of motion requiring release of adhesions). Interestingly, the rate of ulnar nerve complications was similar to that observed for primary UCL reconstruction. Marshall *et al.* compared 33 Major League pitchers who underwent revision UCL reconstruction with age-matched controls and found a low rate of return to sport (66%) and shortened careers after return to sport (minus 0.8 years).[74] Although various statistics of performance were maintained (earned run average, walks/hits per innings pitched), pitchers returned with a significantly decreased workload (number of innings pitched). Liu *et al.* recently presented similar results in a retrospective analysis of publicly available Major League data.[71]

No difference has been found in workload between pitchers who did and pitchers who did not require revision surgery after UCL reconstruction, except for total pitch counts, which were lower for pitchers who required revision surgery.[75] In addition, pitchers who required revision surgery underwent primary reconstruction at an earlier age and had less Major League experience. In a different study, comparing a group of pitchers who underwent primary UCL reconstruction and subsequently required revision surgery with a group of pitchers who did not require revision surgery, the revision group was observed to pitch at or above their preprimary UCL reconstruction workload, whereas the non-revision group pitched significantly less, i.e., below their pre-UCL reconstruction workload.[76]

New developments and the revival of UCL repair

As UCL reconstruction is reaching its full potential as a surgical intervention, current research is focusing on alternative interventions for UCL injuries to further improve outcomes and decrease time to return to play. Recent developments include the utilization of orthobiologics and advanced UCL repair methods, including internal bracing.[77]

The use of biologics to stimulate and enhance tissue healing has garnered increasing attention in sports medicine.[19] Platelet-rich plasma (PRP) is an ultra filtrate of autologous blood with high concentrations of platelets, resulting in an increase in the number of growth factors.[78] These growth factors theoretically act as chemoattractants involved in cell proliferation and immune cell regulation, having the ability to stimulate endothelial growth and angiogenesis.[79] Numerous studies have demonstrated the ability of PRP to heal damaged tissue, including medial collateral ligament injuries of the knee, elbow tendinitis, and Achilles tendon tears.[80,81] Podesta *et al.* recently reported the clinical outcomes of 34 patient undergoing a single PRP injection for partial UCL tears and concluded that PRP is a viable and safe option for young athletes, older recreational athletes or in-season professional athletes with partial tears who do not want to undergo a season-ending UCL reconstruction.[82] They reported promising results, with return to play in thirty athletes (88%) at an average of 12 weeks after injection. In addition, significant findings were noted for improved clinical outcomes and decreased medial joint space opening to valgus load. Recently, Dines *et al.* reported successful results using PRP injections for partial tears in competitive throwing athletes.[83] Further research on dosage, number and timing of injections, composition of the ultra-filtrate, ultrasound guidance for injection, and clinical comparison with placebo treatment is needed.[82]

Due to the success of the UCL reconstruction technique, relatively little has been published on UCL repair.[77,84] From a global perspective, UCL repair provides an interesting treatment option, as a substantial amount of UCL injuries outside of the US does not involve the poor quality native ligament tissue that is generally observed in baseball pitchers. Although UCL repair has initially been reported to lead to suboptimal results with a return to sport rate of 71%, in some patients, this treatment option may offer similar results as UCL reconstruction with the advantage of a shorter rehabilitation time.[25,77,85] Dugas reported that the UCL reconstruction technique is currently applied in patient with a wide range of UCL pathology - from partial undersurface tearing to complete disruption of the ligament - and that there may be a place for UCL repair in athletes with less structural pathology to the ligament, for example, avulsion-type injuries in young athletes or acute hyperextension-valgus trauma in wrestlers and other contact sports.[77]

Outcomes of UCL repair in young patients with avulsion injuries have been described by Savoie *et al.* with good to excellent results in 93% of patients.[86] Biomechanical evidence of UCL repair using the InternalBrace (Arthrex) showed significant improvement of joint stability, with less joint line gapping on de medial side of the elbow compared with the modified Jobe technique.[77,87] This technique may therefore be a viable option for the treatment of end avulsions and partial thickness injuries, with a more rapid return to competition compared with UCL reconstruction. In a 2017 systematic review, Erickson *et al.* reviewed the literature surrounding UCL repair and determined the viability of new repair techniques for the treatment of UCL tears, reporting an overall return to sport rate of over 87% within 6 months after primary UCL repair.[86,88] Clinical studies evaluating UCL repair with internal bracing versus UCL reconstruction in patients from different disciplines are necessary before definitive recommendations can be made.[88]

Conservative treatment of UCL injuries

Although literature on this topic is sparse, there is evidence that UCL injuries may be successfully managed with rehabilitation, especially when involving acute, partial, traumatic UCL tears in non-throwing athletes.[12,89,90] In general, conservative treatment should be exerted before considering surgical intervention in incomplete UCL tears. Conservative treatment typically consists of early management of pain and inflammation and gradual increase of elbow range of motion, followed by a progressive strengthening program, including the elbow, trunk, and shoulder musculature.[91] The final phase of rehabilitation emphasizes dynamic strengthening of the upper extremity and includes an interval throwing program.[92]

Ford *et al.* assessed the correlation between return to play rates following non-operative treatment and radiological findings on MRI in professional baseball players with UCL injuries and found a return to sport rate in players with incomplete UCL injuries of 84% (26/31).[93] In 2001, Rettig *et al.* reported a significantly lower success rate with only 42% (13/31) of overhead athletes returning to their previous level of sport after following a supervised rehabilitation program, with no significant difference between acute injuries and injuries with an insidious onset.[89]

The lessons learned

The introduction of the UCL reconstruction technique in 1986 may be one of the most successful orthopaedic inventions of the 20th century. Without this procedure, the careers of overhead throwing athletes are at high risk to come to an abrupt and premature end. After 30 years of alterations and modifications, the surgical procedure for UCL injuries appears to have reached its full potential. However, one in five pitchers still do not make it back to their previous level of sport after undergoing reconstruction of the UCL. To improve outcomes of elbow injuries in overhead athletes, our emphasis should be on primary and secondary prevention, evidence-based rehabilitation, and the development of individualized return-to-play criteria for the upper extremity.

The notable increase in medial elbow pain, UCL injuries, and UCL reconstructive procedures performed in young overhead athletes over the past decades is especially worrisome because of our lack of knowledge about longterm outcomes after surgical intervention. The durability of the autograft is unknown and current numbers of reinjury of the UCL after reconstruction are relatively high. With an increasingly young population undergoing UCL reconstruction, the absolute number of athletes who suffer reinjury of their elbow requiring secondary surgery is expected to rise substantially over the coming decades, with uncertain consequences for their careers.

Supra-physiological high forces at the level of the medial elbow are probably inevitable when performing an overhead throwing motion, and we may consider 'throwing a couple of dozen (sub)maximal pitches in a short period of time' as unnatural behavior. Therefore, a certain amount of wear and tear of the medial structures of the elbow may be unavoidable in overhead throwing athletes. More than throwing velocity and pitch count, it may be the allowance of sufficient time to recover that is paramount to prevent permanent and irreversible damage to the UCL. It may well be that it is this factor ('rest') that is abused in young athletes to date, leading to early structural changes of the UCL, resulting in increased vulnerability to tearing of the UCL. Parents, coaches, trainers, and medical professionals should be aware of the necessity of rest and enforce healthy recovery behavior in their throwing children, pupils, and patients.

Conclusion

A combination of urgency, limited alternatives, and desperation led to the experimental surgical procedure performed on the elbow of pitcher Tommy John in September, 1974 by the late Dr. Frank W. Jobe (1925-2014). This invention incited a new era in professional baseball and sports medicine, as tearing of the UCL was no longer career-ending. Nowadays, UCL reconstruction surgery saves many careers, with success rates higher than 80%, allowing athletes from different levels of sport to keep up their level of play. However, rehabilitation after primary UCL reconstruction still requires up to 18 months and revision surgery is performed in approximately 15% of patients. Furthermore, the incidence of medial elbow complaints and the number of performed UCL reconstructions are rising, especially in young amateur and adolescent athletes. An increased workload at younger age (increasing throwing velocities, early single sport specialization and socioeconomic incentives to maintain performance) as well as false public perceptions regarding UCL surgery may be contributing factors. This worrisome trend requires attention and supports research into primary prevention, early detection, and conservative treatment of elbow injuries.

Additional expert opinion

We asked two leading orthopaedic surgeons and authorities in the field of elbow injuries, Dr. James R. Andrews (Gulf Breeze, Florida, USA) and Prof. Dr. Roger van Riet (Antwerp, Belgium), for their opinion on the current 'epidemic' of UCL injuries, return to sport decision-making, the development of novel treatment modalities, and preferred surgical technique for UCL reconstruction (*Supplemental material*, page 48-53).

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Supplemental material: expert opinions

Dr. James R. Andrews
ORTHOPAEDIC SURGEON
CHAIRMAN & MEDICAL DIRECTOR OF THE AMERICAN SPORTS MEDICINE INSTITUTE

What is your take on the rising incidence of UCL reconstructions performed in young overhead athletes in the United States?

A major reason that we are seeing more injuries than ever is the fact that athletes are getting bigger, taller, and faster and - because of that - they put more stress on their elbow. Their tremendous muscle development overdoes their ligament development. In other words, when they are a high school senior, they are often throwing 90 mph and their ligament in early development is not ready to take that kind of high stress. Some of the elite ones in high school are throwing close to or at 100 mph. Research that we have done at ASMI indicates that the "redline" of the UCL in high school is around 80 mph and anything over 85 mph becomes suspect. As I said, the UCL is a developmental ligament and gets stronger with throwing and gradual applied stress until they are about age 26 or so. Because of the emphasis on the radar gun and velocity in high school, we are seeing a markedly increased number of kids with UCL injuries. The largest number of UCL reconstructive surgeries in the past was in the professional ranks at the Major Leagues. The next level was the Minor Leagues, then college, and the least in elite high school players. Now, the high school players are the largest group with UCL injuries over all the other subgroups including the Major League players.

Do you expect this trend to continue or stabilize?

Unfortunately, I don't see this stabilizing. There is a lot of work being done relative to prevention. However, prevention falls upon deaf ears and there is very little change being done related to the culture associated with youth baseball. There has been a lot of work done at the professional level trying to minimize the stresses across the elbow and to decrease fatigue, which hopefully will help diminish the injuries that we see at the professional level. Further follow-up will be the only way to bear this out. Hopefully, we will be able to gradually get control of this epidemic rise of UCL injuries at all levels of baseball, but as of right now it is still only hope.

How do you determine return to sport after UCL reconstruction and who is involved in the return to sport decision making?

The determination to return to sport generally is determined by the length of time since the surgery was done. In general, for high school and college throwers it takes about 12 months. At the Major League level, it usually takes about a year and a half. It is a know fact that they are much better the second year back than the first year. There are many factors that determine the return to play, which includes an adequate physical exam and adequate progression through various steps in the rehabilitation process. That includes basic rehab, then interval flat-ground throwing, and - for a pitcher - a mound program. After the mound program, they have to progress to throw simulated games and throwing at a lower level. The final decision to return to play is also based on objective upper extremity functional testing. This is done in the physical therapy department and determines strength, flexibility, and fatiguability.

The final decision though is based on the surgeon's willingness to determine that they are ready to return to play. Return to play is a catchy term. Does that mean return to practice or does that mean return to high level competitive throwing (which should be specific to that particular player's level of play)? Of course, when this decision is being made, it is also made with the other members of the athletic medical team, including the physical therapist, athletic trainer, strength, conditioning, and the pitching coach alike. It is a team decision, but final say so obviously is the surgeon.

What is your take on new developments for the treatment of UCL injury, such as PRP (platelet-rich-plasma) injection and internal bracing?

We are beginning to get some basic research done and some follow-up results on PRP for lower grade UCL tears. PRP is primarily used for low-grade partial tears, particularly in the younger age group. In this population, the ligament is relatively fresh and not injured to any great degree. Sometimes it is done in the junior high and high school level just to get the players and parents to shut the patient down from throwing for a significant period op time, to allow them to heal and to become asymptomatic. PRP though, is used in all of the different groups for partial tears and has been effective in some recent research studies. It is still not 100% successful and we still don't know the results of PRP over the long haul.

Recent excitement related to internal bracing is even less researched and is very new relative to when it should be used and what will be the long term results of it. Further research and follow-up is needed before we extrapolate those procedures to more serious ligament injuries, especially in older age group professional players. Right now, the research has mostly been done on young high school players with relatively sound overall ligament structures with small partial tears. In this group of low-grade tears it is showing promising results. More time is needed though before its use can be expanded into the more complex ligament injuries, especially in the older age group of throwing athletes.

Is there a topic that is underexposed in current elbow injury research that deserves more attention?

I think a big thing that we want to know is how we can enhance the biological healing properties of a UCL reconstruction using an autogenous graft. If we can do that, perhaps research will show that we can use an allograft (cadaver graft). By using stem cell therapy, we might be able to get the cadaver grafts to heal as well as an autograft. In the meantime, we are all looking for means to get these athletes well quicker and get them back into their sport, so they don't miss a whole season and perhaps - in some cases - two seasons. That research is still underway and as of this particular writing, we don't have any clear basis to make any claims relative to biologic healing enhancement using stem cell therapy at the time of the surgical procedures. Its use does, however, appear promising.

Prof. dr. Roger van Riet
PROFESSOR OF ORTHOPAEDIC SURGERY
PRESIDENT OF THE BELGIAN ELBOW & SHOULDER SOCIETY

What is your take on the rising incidence of UCL reconstructions performed in young overhead athletes in the United States?
This is a complex question. All conservative measures should be exhausted before surgery is considered. This includes prevention, decreased stress on the elbow, improved technique, and stricter rules on the frequency of elbow loading sporting activities. Once symptoms have appeared, sufficient rest, followed by a strengthening program and slow return to sports should be attempted for a minimum period of 6 to 12 months. However, significant pressure is placed on young athletes to perform at a high level at a young age and to return to sport as soon as possible once an injury has occurred. Young athletes in the US may have an alternative reason to pursue aggressive treatment, as a scholarship may be on the line for a future college degree.

I am sure that most surgeons consider all the pros and cons carefully and will advice against surgery unless absolutely indicated. So, if the rising incidence is because more young athletes are injured, than more time and effort should be spent on prevention and conservative measures. If the rising incidence is because surgeons are becoming less strict when determining their indication, then maybe national guidelines should be drafted to avoid unnecessary surgery.

Do you expect a similar trend in Europe?
No, I don't expect a similar trend in Europe. In Europe, overhead sporting activities are, in general, less high profile when compared to the US. Furthermore, in most European countries, sports are not a way to get a college education. This means that there is much less pressure on timing of surgery. Many patients do well with conservative treatment if symptoms are detected early and patient get optimal treatment, including changing their technique or position in the field. A large portion of young athletes may avoid surgery with prolonged conservative therapy if they are allowed to invest the time it takes.

How do you decide on operative or non-operative treatment of UCL injury in throwing athletes?
The decision to perform surgery is always multifactorial. There is a large difference between acute injuries, chronic injuries, or acute-on-chronic injuries. Injuries from an acute trauma, even in overhead athletes, are often treated successfully with acute reinsertion. Chronic symptomatic injuries are treated conservatively in most patients. The decision to perform surgery does not only depend on the severity of symptoms but also depends on age, level of sports, and the ambition of the patient. Conservative treatment does not burn any bridges, so I always discuss this option with all patients.

In professional athletes, we assume adequate technique, strength, and coordination and there is definite time pressure on the patient. Professional athletes are therefore often treated more aggressively after discussing both conservative and surgical options. Literature shows that conservative treatment in this patient group does not lead to return to sport at the same level in over 50% of patients. If these athletes are unable to perform at their normal level, despite pain relief and anti-inflammatory measures, surgery may be indicated. Timing is often determined by the timing in the season or even the next season, keeping in mind that postoperative rehabilitation will take more than 6 months.

Which technique for UCL reconstruction do you prefer and what are your considerations?
My preferred technique depends on the sport of the patient and the mechanism of injury. Athletes with extreme valgus forces on their elbow, such as javelin throwers, often have an acute-on-chronic injury mechanism. In these patients, there is a degenerative tear or avulsion with poor quality remaining tissue. The ligament needs to be reconstructed as strongly as possible. My preferred graft is an extensor hallucis longus allograft, as it is very predictable with respect to strength, length, and width and avoids any comorbidity that may occur from harvesting an autograft. The medial elbow is approached through a flexor split. The ulnar nerve is released but not transposed. The graft is pulled through and ulnar tunnel and fixed with a modified docking technique in a narrow humeral tunnel under maximal tension. The graft is sutured to itself and to any remaining UCL tissue. The flexor split is closed and sutured to the graft as well.

In chronic injuries without acute onset, where conservative treatment failed, the remaining tissue is insufficient and needs strengthening. This is relatively common in professional tennis players. In these patients, I have developed a different approach to decrease the time to return to sport. The same flexor split is used but the ulnar nerve is not released and no bone tunnels are used. In this way, the native UCL can remain intact and there is no need to disturb its bony insertions. Instead, 1.4 all-suture anchors are placed in both the humeral and ulnar UCL insertion. The same extensor hallucis longus graft is folded over the remaining UCL. Depending on the thickness of the graft, we typically use a three- or four-strand reconstruction. The graft is fixed firmly at the ulnar anchor and tensioned using the humeral sutures. The native UCL is imbricated and sutured to the graft. Sutures of both ulnar and humeral anchors are then tied together as a non-biological reinforcement of the reconstruction. The flexor split is closed and sutured to the graft.

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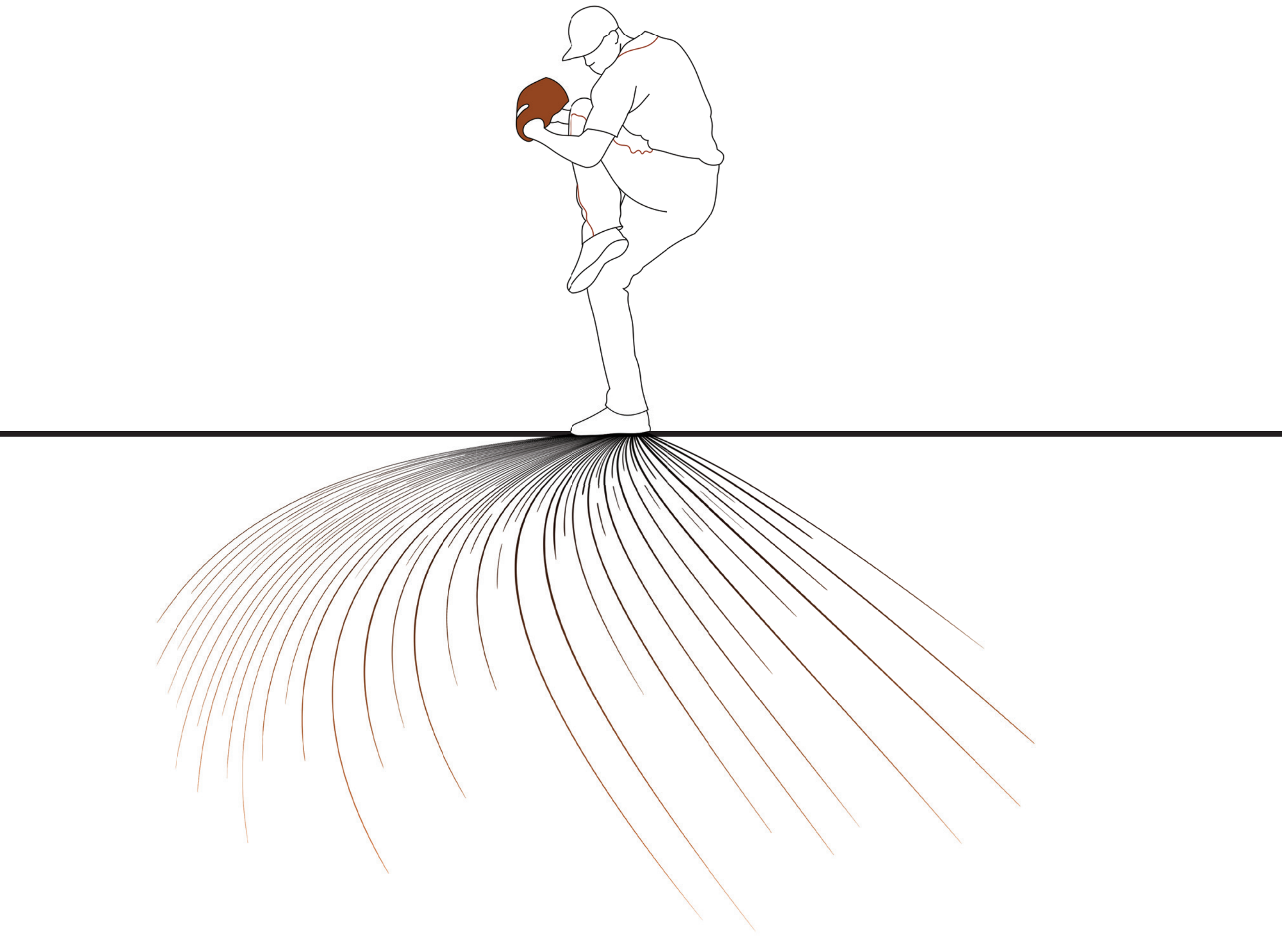
PART II

CLINICAL WORKUP OF UCL INJURY IN OVERHEAD ATHLETES



3

Clinical value of an acute popping sensation in throwing athletes with medial elbow pain for ulnar collateral ligament injury

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Mark R. Nazal
Denise Eygendaal
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ABSTRACT

Background
Throwing athletes sustaining an ulnar collateral ligament injury may recall a popping sensation originating from the medial elbow at the time of injury. There are no studies available that inform clinicians how to utilize this salient anamnestic information and what amount to diagnostic weight to afford to it.

Purpose
To assess the diagnostic value of a popping sensation for significant UCL injury in throwing athletes who sustained an injury causing medial elbow pain.

Methods
A total of 207 consecutive patients with throwing-related medial elbow pain were evaluated for UCL injury by the senior author between 2011 and 2016. The presence or absence of a popping sensation was routinely reported by the senior author. Magnetic resonance imaging was evaluated for UCL injury severity and classified into intact, edema/low-grade partial-, high-grade partial-, and full-thickness tears.

Results
The overall frequency of a pop was 26%. The proportion of patients who reported a pop significantly increased with UCL tear severity ($P < .001$), from 13% in patients with low-grade UCL injuries to 26% in patients with high-grade partial-thickness tears and 51% in patients with full-thickness tears. The positive likelihood ratio, negative likelihood ratio, and odds ratio of a popping sensation for significant UCL injury were 3.2, 0.7, and 4.4, respectively ($P < .001$). A pop was not associated with either distal or proximal UCL tears ($P \geq .999$).

Conclusion
A popping sensation at the time of injury in throwing athletes with medial elbow pain was associated with UCL injury severity. When a throwing athlete reports a pop, this should moderately increase a clinician's suspicion for a significant UCL injury. Conversely, absence of a pop should not substantially decrease suspicion for significant UCL injury. The findings of this study allow for the clinical interpretation of the salient anamestic finding of a pop at the time of injury, which can be used for diagnostic purposes as well as patient counseling. This study provides reference foundation for future studies of predictive and diagnostic factors for UCL injury in throwing athletes.

Introduction

Ulnar collateral ligament (UCL) injuries of the elbow are increasingly common in overhead throwing athletes and usually affect the anterior bundle.[2,5,7,11,14,15] As with most orthopaedic injuries, the assessment of medial elbow pain includes a thorough history and physical examination. Throwing athletes sustaining a UCL injury may recall a popping sensation (feeling or hearing) originating from the medial elbow at the time of injury (figure 3.1). Athletes may tell clinicians when they felt a pop, but there are no studies available that inform clinicians how to utilize this information and what amount of diagnostic weight to afford to it.

A plausible explanation of the popping sensation is an acute disruption of tissue fibers, which may be intuitively associated with a tear. The proximal and distal attachments of the UCL are histologically different - with the proximal attachment to the anteroinferior medial epicondyle having a more perpendicular orientation and with the distal attachment having a more angular orientation - but it is unknown if the popping sensation is related to UCL tear location.[3,4,8,10] It has been suggested that distal UCL tears have poorer outcomes when managed nonoperatively as compared with proximal tears.[9,10] Correlations between UCL tears and anamnestic characteristics, such as the occurrence of a pop, could inform not only the presence of a tear but also the location and therefore its management. A pop at the time of injury has been shown to be one of the factors that can be used to screen for anterior cruciale ligament lesions of the knee, with high diagnostic validity for partial and complete tears.[6,17]

The purpose of this study was to assess the diagnostic value of the subjective experience of a popping sensation for significant UCL injury among

Figure 3.1
Throwing athletes sustaining an ulnar collateral ligament injury may recall a popping sensation originating from the medial elbow at the time of injury.

throwing athletes who sustained an injury causing medial elbow pain. In addition, we examined the association of a popping sensation with UCL tear severity and explored whether a pop is associated with tears at either the proximal or distal attachment site of the anterior bundle of the UCL. The hypothesis was that the occurrence of a popping sensation increased the likelihood of a significant UCL tear in throwing athletes with medial elbow pain and was associated with higher tear severity.

Materials & methods

Study sample

This study was approved by the Partners Human Research Committee of Massachusetts General Hospital. The institutional Research Patient Data Registry was searched with *International Classification of Diseases* code 8411 (Ninth Revision) and codes S53.3 and S53.44 (Tenth Revision) and with Current Procedural Terminology codes 24345 and 24246 to identify patients evaluated for concern of UCL injury. A total of 384 patients with medial elbow pain were evaluated at our institution between 2011 and 2016, including 207 consecutive overhead athletes evaluated by the senior author (LSO) for UCL injury.

All medical records were reviewed and assessed by the first author (RJM) and the last author (LSO) using the electronic medial record system (QPID Health Inc). The following data were obtained from the medical records: sex, age, race, hand dominance, side of injury, type of sport, level of play, symptoms onset, and the occurrence or absence of a popping sensation at the time of injury. The senior author routinely asked patients if they did or did not feel a pop at the time of injury and reported either outcome.[*] Patients included in the analysis underwent diagnostic magnetic resonance imaging (MRI) assessment (1.5 or 3.0 Tesla) as part of standard clinical workup, which a fellowship-trained musculoskeletal radiologist specifically evaluated for suspected UCL anterior bundle pathology. MRI results were evaluated after the senior author had obtained the history and performed physical examination.

UCL tear severities were classified into four categories, according to the MRI-based classification for UCL injuries by Joyner *et al.*: intact; edema, waviness, low-grade partial-thickness tears; high-grade partial-thickness tears;

* Transcrips from medical records subsequently reporting the occurrence and the absence of a popping sensation at the time of injury:

"Patient A is a very pleasant 18-year-old right-hand-dominant male pitcher seen for consultation regarding right elbow pain. He was helping a pitcher warm-up 4 weeks ago with a long toss of roughly 150 feet, when after one throw he felt the immediate onset of mediale elbow pain. He felt a pop in the area as well. ..."

"Patient B is a 21-year-old right-hand-dominant male pitcher. He states that he felt a sudden pain in his medial elbow after a pitch in the 4th inning of the first game of the year. He did not feel a specific pop at the time of injury. He continued to pitch for several pitches afterwards, however, his velocity was down and he continued to have pain. ..."

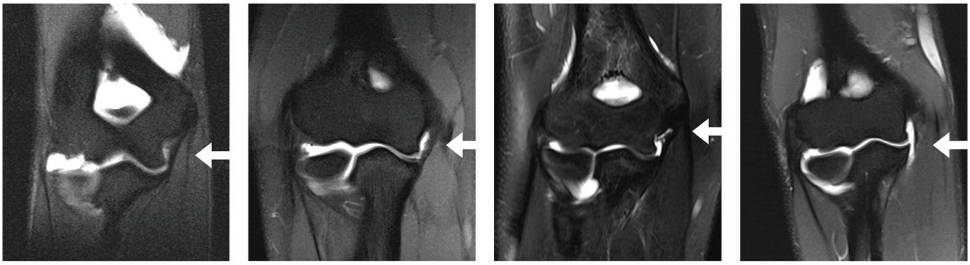

Figure 3.2 MRI-based classification of ulnar collateral ligament injuries (white arrows) into 4 categories: intact; edema or low-grade partiale thickness tears; high-grade partial-thickness tears; and complete full-thickness tears.

and complete full-thickness tears (figure 3.2).[12] To quantify the diagnostic value of a pop, high-grade partial- and complete full-thickness tears were defined as significant UCL injury.

Statistical analysis

Data were described with frequencies and percentages for dichotomous and categorical variables, means and standard deviations for normally distributed continuous data, and median and interquartile range for nonparametric continuous data. Two-sided Fisher exact tests were used for the comparison of the frequency of a popping sensation among the four UCL tear severity categories, including post hoc comparisons, and for the assessment of a relationship between a pop and UCL tear location.

A 2 x 2 contingency table of the occurrence of a pop versus significant UCL injury (defined as a high-grade partial- or full-thickness UCL tear) was used to calculate the prevalence, sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), positive likelihood ratio (LR+), and negative likelihood ratio (LR-) of the subjective sensation of a pop for significant UCL injury, including 95% confidence intervals (CI). Logistic regression analysis was used to calculate the odds ratio (OR), including 95% CI and P value. According to McGee *et al.*, a LR+ >5 and a LR- <0.2 represent relatively important effects; LRs between 0.2 and 0.5 and between 2 and 5 may be important; and values close to 1.0 represent unimportant effects.

The false discovery rate was used to correct for multiple comparisons (pop versus UCL injury severity and tear location; OR).[1] Adjusted *P* values <.05 were considered statistically significant. Statistical analysis was performed with STATA/SE 14.2 statistical software (StataCorp LP).

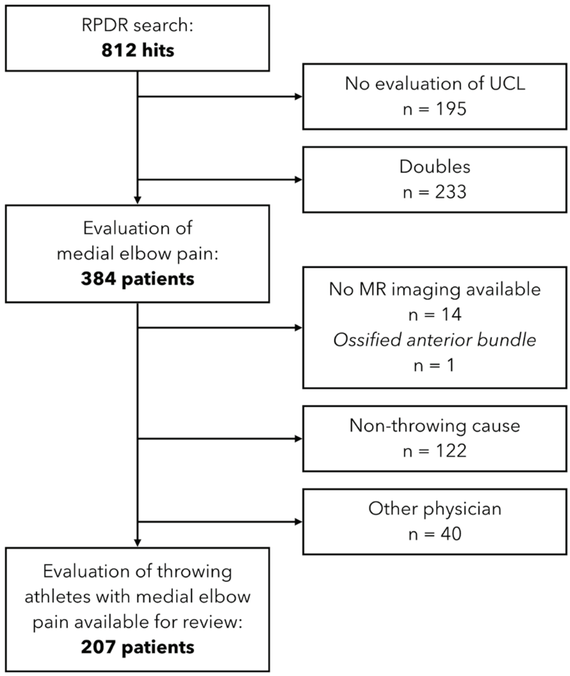

Figure 3.3
Flowchart of the study sample, including patients who underwent magnetic resonance imaging and excluding patients with non-throwing causes of injury and patients who were not treated by the senior author. *RPDR*, Research Patients Data Registry; *MR*, magnetic resonance*; UCL*, ulnar collateral ligament

Table I. Patient characteristics (n = 207).

Variable	**n**	**(%)**	**Variable**	**n**	**(%)**
Male sex	201	(97)	Sport		
Age, y, mean ± SD	19.2	± 3.7	Baseball	194	(94)
Race			Pitcher	162	(84)
White	186	(90)	Catcher	11	(5.7)
Hispanic	6	(2.9)	Other position	21	(11)
Asian	4	(1.9)	Javelin	7	(3.4)
Unknown	11	(5.3)	Softball	5	(2.4)
Dominant-side injury	207	(100)	Quarterback	1	(0.5)
Symptom onset			Level of play		
Acute	92	(44)	High school	92	(44)
Subacute	43	(21)	Collegiate	103	(50)
Acute-on-chronic	19	(9.2)	Professional	8	(3.9)
Chronic	50	(24)	Recreational	4	(1.9)
Unknown	3	(1.5)			

y, years; *SD*, standard deviation

Results

Demographics

The flowchart of the sample selection process is shown in figure 3.3. A total of 207 consecutive overhead athletes with medial elbow pain evaluated by the senior author for UCL injury were available for review and included for analysis. The demographic characteristics of the study sample are summarized in table I. The study population included mainly white male baseball pitchers at the high school or collegiate level. MRI with intra-articular contrast was performed in 136 of 207 patients (66%), and 71 patients underwent MRI without contrast (34%).

Popping sensation and UCL tear severity

The overall prevalence of a pop in our study population was 26% (95% CI, 20%-32%). Among the subgroup of patients who experienced an acute moment of injury (acute or acute-on-chronic onset of symptoms), the prevalence of a pop was 46% (51 of 111). There were 10 patients without UCL injury (4.8%), 72 with edema/low-grade partial-thickness tears (35%), 80 with high-grade partial-thickness tears (39%), and 45 with complete full-thickness tears (22%). The proportion of patients who reported a pop significantly increased with UCL tear severity (*P* <.001; figure 3.4), from 13% in patients with low-grade UCL injuries (9 of 72) to 26% in patients with high-grade partial-thickness tears (21 of 80) and 51% in patients with full-thickness tears (23 of 45).

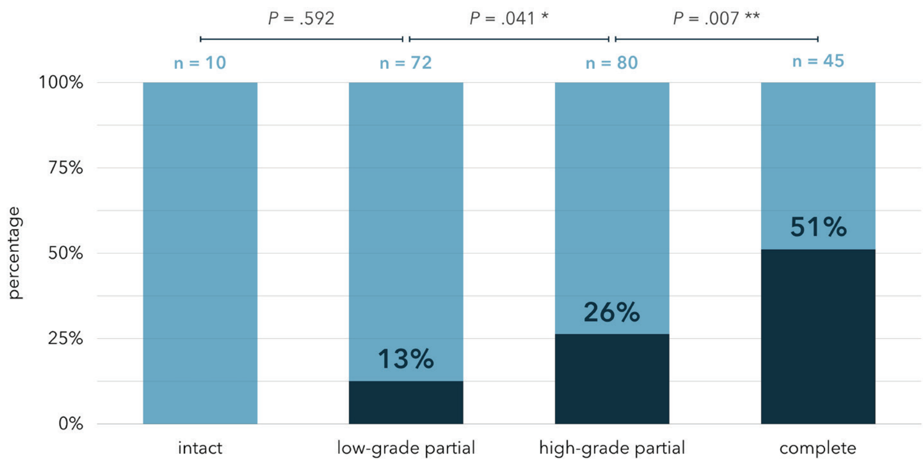

Figure 3.4 The proportion of patients who felt a pop significantly increased among ulnar collateral ligament injury severity groups.

Table II. Contingency table (2 x 2) of a popping sensation versus UCL injury severity.

	UCL tear severity		
	≤ low grade	≥ high grade	total
pop	9	44	53
no pop	73	81	154
total	82	125	207

Data are reported as No. *UCL*, ulnar collateral ligament

Quantification of popping sensation

Table II shows the frequencies of a popping sensation among high-grade UCL injury (high-grade partial-thickness or full-thickness) and low-grade UCL injury (intact or low-grade partial). The sensitivity and specificity of a popping sensation for significant (i.e., high-grade) UCL injury were 35% (95% CI, 27%-44%) and 89% (95% CI, 80%-95%), respectively. The PPV was 83% (95% CI, 70%-92%), and the NPV was 47% (95% CI, 39%-56%). The LR+ was 3.2 (95% CI, 1.6-6.2), and the LR- was 0.7 (95% CI, 0.6-0.9). The OR of a popping sensation for significant UCL injury was 4.4 (95% CI, 2.0-9.5; P <.001).

Popping sensation and UCL tear location

A total of 125 patients showed a high-grade partial-thickness or complete full-thickness UCL tear on MRI (60%). Of these tears, 92% (115 of 125) were located at either the distal or the proximal attachment site of the anterior bundle. The remaining 8.0% had a tear of the midsubstance or multiple tears of the anterior bundle and were excluded from this analysis. A popping sensation was not associated with either distal or proximal tears (36% versus 35%; $P \geq .999$).

Discussion

In this study, we examined the clinical value of the subjective experience of a popping sensation at the time of injury for significant UCL injury of the anterior bundle in throwing athletes. In our sample, one in four patients experienced a popping sensation (26%), with a prevalence of 46% among patient who had an acute or acute-on-chronic onset of medial elbow pain that resulted in immediate inability to throw. Based on MRI, 60% of patients had a significant UCL injury of the anterior bundle, defined as high-grade partial-thickness tears or complete full-thickness tears. We observed a significant increase in frequency of a popping sensation among UCL tear severity groups, up to 51% in patients with complete full-thickness tears ($P < .001$). Although the proximal and distal attachments of the UCL are histologically different, this appears to be unrelated to the phenomenon of generating a popping sensation, as no relationship was observed between a pop and UCL tear location ($P \geq .999$).[3,4,8,10]

Clinical interpretation of a pop

For quantification of the popping sensation, we were especially interested in the LRs and OR, as they reflect the predictive ability of the popping sensation for UCL injury and do not depend on disease prevalence. This means that the observed LRs in this study are applicable to other clinical settings if the definition of significant UCL injury is not changed (high-grade partial thickness and complete full-thickness UCL tears).[16] The feeling or hearing of a pop increased the odds of a high-grade UCL injury in throwing athletes with medial elbow pain by 4.4 times (OR; $P < .001$). Our findings suggest that a pop is three times more likely to be reported by patients with high-grade partial- or full-thickness UCL tears as compared with patients with low-grade or no UCL injury (LR+). The absence of a pop was 0.7 times less likely in patients with significant UCL tears as compared with patients with low-grade or no UCL injury (LR-). This means that the reporting of a popping sensation moderately increases the likelihood of a high-grade UCL injury, but the absence of a pop should not substantially decrease clinical suspicion for high-grade UCL injury (figure 3.5). This finding is also reflected by the low sensitivity (35%) and high specificity (89%) of a pop for significant UCL injury.

In our sample, patients who reported a pop had an 83% chance of having significant UCL injury (PPV). Conversely, patients who did not report a pop had a 47% chance of having significant UCL injury (NPV). However, it needs to be considered that these predictive values largely depend on the prevalence of high-grade UCL injury in the examined population; therefore, generalization of these values is limited to settings with a similar prevalence (e.g., tertiairy referral centers for throwing athletes in the United States).[16] In settings with a lower prevalence of high-grade UCL injuries, PPV will decrease and NPV will increase (whereas the decrease in PPV will be more substantial).[16]

Limitations

In addition to the sensitivity of measures of diagnostic accuracy to disease prevalence and disease definition, there are some limitations of this study that require consideration. First, our sample included mainly male baseball pitchers, which may limit the generalizability of our findings to other types of athletes. A second limitation of our study is the retrospective nature of the assessment of UCL tears based on available MRI. The clinical assessment of MRI limits the level of detail of our observations regarding tear characteristics presented in this study. However, experienced musculoskeletal radiologists at our institution

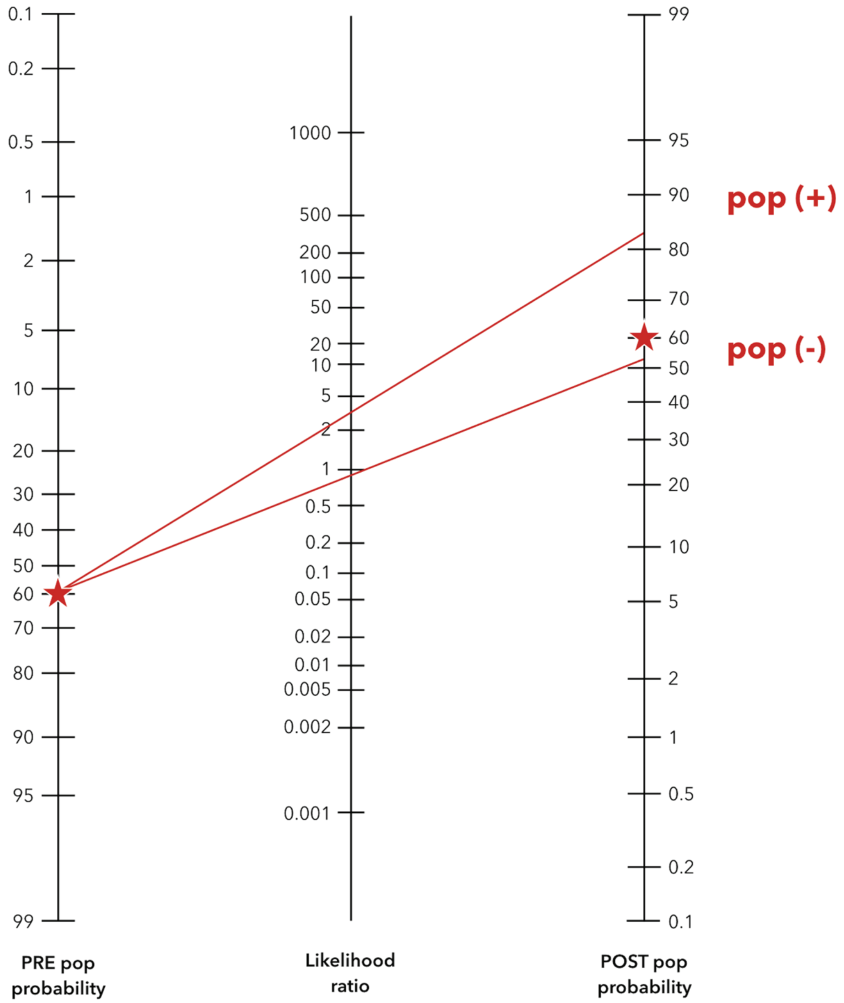

Figure 3.5 Bayes nomogram of positive (3.2) and negative (0.7) likelihood ratios of a popping sensation for high-grade UCL injury of the anterior bundle, reflecting a moderate increase in likelihood from 0.60 to 0.83 in patient who reported a popping sensation and a non-substantial decrease from 0.60 to 0.53 in patient who did not.

assessed all MRI. A third important consideration and avenue for future research is the fact that this study focused on the subjective sensation of a pop as an isolated factor. In clinic, physicians collect a variety of factors, from history taking as well as physical examination, and weigh these to determine a patient's risk of disease or injury. Therefore, future multifactorial studies, including physical examination findings, should be able to determine the diagnostic value of the salient anamnestic finding of a pop in throwing athletes with medial elbow pain in combination with other factors that may predict UCL injury severity. Last, in this study, we did not observe that tear grade was associated with tear location (distal versus proximal injury). However, this analysis may have been limited by the smaller subcohort sample size of distal and proximal high-grade UCL injuries (n = 115), and future prospective studies with larger sample sizes may further delineate any associations.

Taking the limitations of the current study into consideration, we believe that this is the first study addressing the salient finding of a popping sensation in throwing athletes with medial elbow pain - a phenomenon that is well known by physicians treating these athletes - quantifying the subjective experience of a pop at the time of injury for the likelihood of significant UCL injury of the anterior bundle.

Conclusion

The subjective experience of a popping sensation at the time of injury in throwing athletes with medial elbow pain was associated with UCL injury severity but not UCL tear location. When a throwing athlete reports feeling or hearing a pop, this anamnestic finding should moderately increase a clinician's suspicion for significant UCL injury. Conversely, the absence of a pop should not substantially decrease clinical suspicion for a significant UCL tear. This study provides a reference foundation for future studies of predictive and diagnostic factors for UCL injury in throwing athletes.

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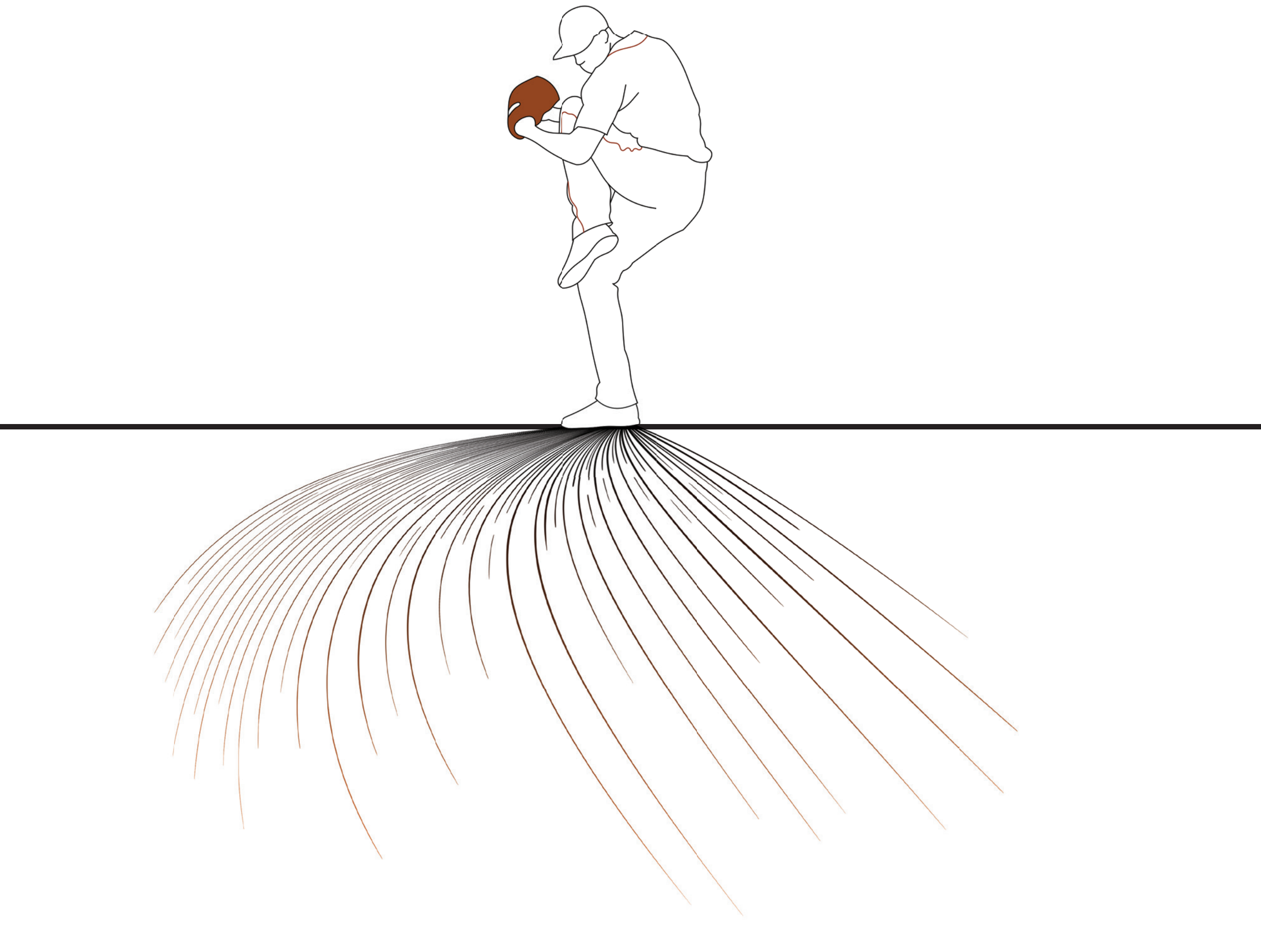

4

Injured versus uninjured elbow opening on clinical stress radiographs and its relationship to UCL injury severity in throwers

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ABSTRACT

Background
Stress radiography measures medial joint space opening of the elbow, but its value in the management of throwing athletes is unclear. The purpose of this study was to analyze the relationship between medial joint opening (gapping and excess opening) and ulnar collateral ligament injury severity on magnetic resonance imaging, as well as to explore factors related to the unexpected finding of a greater opening of the uninjured elbow compared to the injured elbow with valgus stress radiography (negative excess opening).

Methods
Medial joint space measurements were independently performed by two raters in a clinical series of seventy-four patients evaluated with standardized valgus stress radiography as part of their clinical workup for throwing-related medial elbow pain. Demographic data were collected by chart review and UCL injury severity was classified based on available imaging into intact UCLs, partial-thickness tears of the anterior bundle, or full-thickness tears of the anterior bundle.

Results
Joint gapping was related to UCL injury severity (P = .003) and group-level comparison showed a difference among tear severity groups (P = .050). Excess opening was not significantly related to UCL injury severity (P = .109). Negative excess opening was observed in 22% of patients, but no factors corroborating guarding or a mechanical explanation were significant for a decreased medial joint opening of the injured elbow compared with the uninjured elbow.

Conclusions
Medial joint gapping was correlated to UCL injury severity in throwing athletes with medial elbow pain and a clinical suggestion of UCL injury, but no association between injury severity and excess opening was observed in this clinical series, which may limit the usefulness of stress radiography in the clinical workup of throwing athletes.

Introduction

The ulnar collateral ligament (UCL) is the main ligamentous stabilizer of the medial side of the elbow and is especially important in the preservation of articular integrity in high-intensity throwers, such as baseball pitchers. In these athletes, maximal loading of the ligament with each pitch it thought to affect its structural integrity and may lead to disruption of tissue fibers, that is, tearing of the UCL, over time.[3] In addition to history taking and physical examination, throwing atletes with a clinical suggestion of UCL injury usually undergo plain radiographs to assess osseous abnormalities at the proximal and distal attachment sites of the UCL (bony or physical avulsions) and magnetic resonance imaging (MRI) with or without contrast to assess soft-tissue injuries, including the structural integrity of the UCL itself.

Over two decades ago, a radiographic method to quantify medial elbow instability using a mechanical stress device was introduced.[13] These stress radiographs allow for the assessment of the functional integrity of the UCL by the medial joint space opening of the elbow. In 2014, Bruce *et al.* published a study presenting the findings of bilateral static and stress radiographs in 273 baseball players with UCL injuries.[2] Using a Telos stress device (SE 2000; Telos, Weiterstadt, Germany) to provide 15 dekanewtons (daN) of stress in a standardized fashion, they observed a larger average medial joint opening with full-thickness UCL tears than with partial-thickness tears. Furthermore, they observed a 0.4 mm greater medial joint opening on the injured side than on the uninjured side. It is interesting to note that 31% of the patients had a negative excess opening, defined as less joint opening on the injured side than on the uninjured side. One theory posed for a negative excess opening is that patients may guard their symptomatic elbow because of pain during the valgus stress radiograph procedure, preventing full (true) opening of the elbow. To date, no studies have examined this "guarding" theory, and no other theories have been proposed to explain a negative excess opening. Over the years, a limited number of studies have been published on the clinical use of stress radiographs and valgus instability assessment in the management of throwing athletes.[2,4-7,9,15,16]

In this study, we examined the findings of stress radiography in a consecutive series of seventy-four throwing athletes with medial elbow pain assessed as part of the standard clinical workup at our institution to evaluate the clinical usefulness of stress radiography. The primary purpose of this study was to analyze the relationship between medial joint opening (gapping and excess opening) and UCL injury severity. We hypothesized that the degree of joint opening would correlate with UCL injury severity on MRI. The secondary purpose of this study was to explore factors related to a negative excess opening, which was expected in approximately 30% of patients.[2]

Materials & methods

This was a retrospective analysis of a clinical series of consecutive patient who underwent stress radiography during the clinical workup for medial elbow pain, with a suggestion of UCL injury. We reviewed the charts and radiographic data of patients with medial elbow pain who had undergone stress radiographs from 2011 to 2016 at our institution. The Research Patient Data Registry was searched using Current Procedural Terminology codes (24345 and 24246) and *International Classification of Diseases, Ninth Revision* or *Tenth Revision* codes (84.11, S53.3, and S53.44) to identify patients examined for UCL injury. From the resulting database, all patients with throwing-related medial elbow pain who underwent Telos stress radiography at our institution, with MRI available for review, were included in this study (n = 79). We excluded five cases in which stress radiography was performed with abnormal flexion position of the elbow, resulting in a final sample of seventy-four consecutive patients eligible for analysis.

Demographic and clinical data were collected, including age, duration of symptoms, elbow range of motion, UCL tenderness to palpation, moving valgus stress test, and flexor-pronator tenderness to palpation. Available MRI data of sufficient quality (1-3 T) were reviewed by two raters (RJM, GISM) for

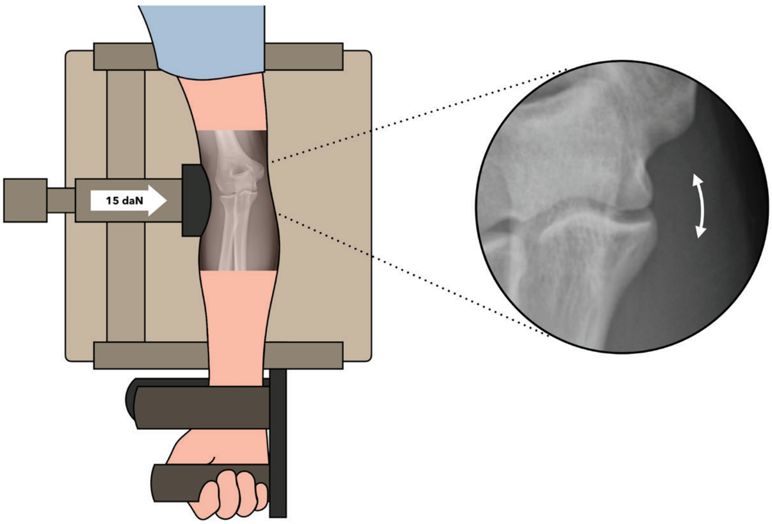


Figure 4.1 Stress views of the injured and unjured elbow were obtained with a Telos stress device to provide 15 dekanewtons (daN) of valgus stress in a standardized fashion (top view, *white arrow* depicting orietnation of force). The patient's elbow was placed in a stress device (20-30 degrees of elbow flexion and full forearm supination) with the patient sitting on a stool and the arm resting on the x-ray table with the shoulder in abduction and external rotation. The patient was instructed to only loosely grip the handle of the Telos device.

severity of UCL injury to the anterior bundle into intact UCLs, partial-thickness tears, and full-thickness tears (complete), as well as flexor-pronator muscle edema and the presence of posterior osteophytes and/or loose bodies.

Standard elbow radiographs performed at our facility for throwing injuries included static anteroposterior, lateral, oblique, and reverse axial (cubical tunnel) views of the injured elbow. Stress and non stress views of the injured and uninjured (only stress view) elbows were performed with a Telos stress device (SE 2000) to provide 15 daN of valgus stress in a standardized fashion. Elbows were placed in the valgus stress device (20 to 30 degrees of flexion and full supination) by a radiology technician with the patient sitting on a stool and the arm resting on the X-ray table with the shoulder in abduction and external rotation in a standardized way (figure 4.1).

Medial joint space measurements were performed using the 1-line method similarly to that described in previous reports.[2,5] The vertical distance from the most distal point of the medial trochlea to the ulnar coronoid parallel to the ulnar axis was measured (figure 4.2). All measurements were performed independently by the first and second author (RJM, GISM) and average values were used as final measurements.

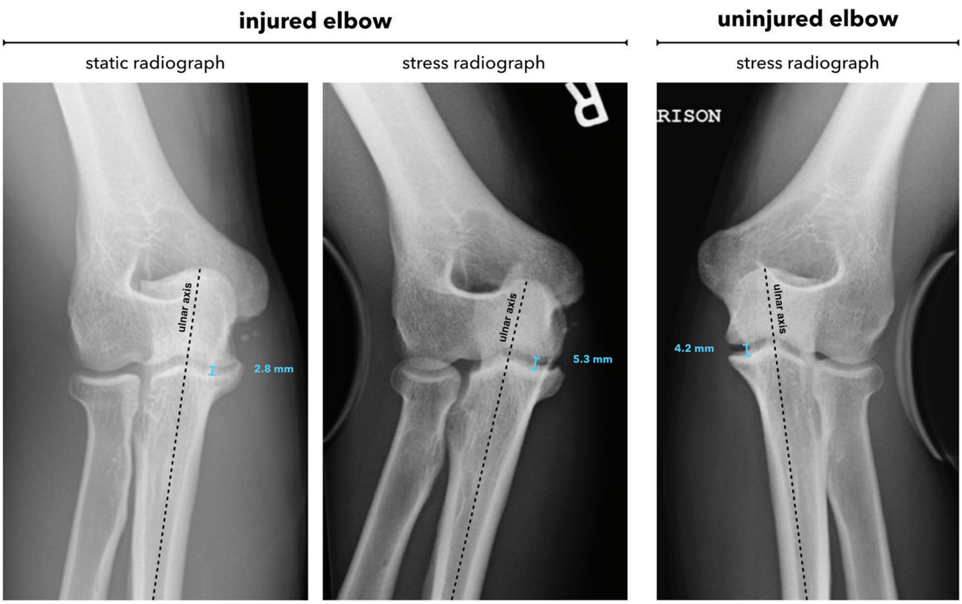


Figure 4.2 Measurements of joint space opening using the 1-line method on static and stress radiographs of the injured (2.8 and 5.3 mm) and uninjured (4.2 mm) elbow of a 22-year-old right-handed pitcher.

On the basis of medial joint space measurements on stress and non stress views, joint gapping (of the injured elbow) and excess opening (of the injured elbow compared with the uninjured elbow) were calculated by simple subtraction. Joint gapping of the injured elbow was calculated by subtracting the joint space distance measured on a static radiograph from the joint space distance measured on a stress radiograph. The uninjured elbow opening on the stress radiograph was subtracted from the injured elbow opening on the stress radiograph to measure excess opening. Excess opening was positive if the joint space distance on the injured side was greater than that on the uninjured side and negative if the reverse was observed.

Measurements were performed on picture archiving and communication system workstations (Centricity PACS, version 2.1; GE Healthcare Systems, Chalfont St Giles, UK) with high-resolution monitors to measure the medial joint space to the nearest 0.1 mm. Intraclass correlation coefficients (ICCs) for the measurements of the injured and uninjured elbows ($ICC_{3,1}$, two-way mixed-effects model) were determined for interobserver agreement. ICC values below 0.50 were considered poor; between 0.50 and 0.74, moderate; between 0.75 and 0.90, good; and above 0.90, excellent.[10] ICC values for the measurements were presented with 95% confidence intervals (CI).

Statistical analysis

Data were described using frequencies and percentages for dichotomous and categorical variables, means and standard deviations (SD) for normally distributed continuous data, and medians and interquartile ranges for nonparametric continuous data. A paired *t* test was used to compare the average medial joint space of injured versus uninjured elbows. Analysis of variance was used to examine differences in mean joint gapping of the injured elbow between patients without UCL tears, those with partial-thickness tears, and those with full-thickness tears. Post hoc pair-wise comparisons were performed using the Fisher exact test with Bonferroni correction. In addition, the Jonckheere-Terpstra test was used to assess an ascending ordinal trend in joint gapping among these groups. Similarly, the Kruskal-Wallis test was used to examine differences in excess opening (injured minus uninjured elbow joint opening) between patients without UCL tears, those with partial-thickness tears, and those with full-thickness tears, and the Jonckheere-Terpstra test was used to assess an ascending ordinal trend in excess opening among these groups. Moreover, subgroup analysis was performed of patients with magnetic resonance (MR) arthrograms and patients who underwent MRI without intra-articular contrast. *P* values were adjusted for multiple comparisons using the false discovery rate correction.[1] Bivariate analysis to explore factors influencing excess opening was performed using the Fisher exact test for binary and categorical outcome variables and the Kruskal-Wallis test for nonparametric continuous outcome variables. Statistical analysis was performed using STATA/SE statistical software (version 14.2; StataCorp, College Station, TX, USA). False discovery rate-adjusted *P* values <.05 were considered statistically significant.

Results

Sample characteristics

The seventy-four patients (73 male and one female patient) included in this study had a mean age of 18.7 years (range, 14.5-24.9 years) at the time of radiographic examination. There were 72 baseball players (97%; 62 pitchers [84%], 4 catchers [5.4%], and 6 position players [8.1%]), one javelin thrower (1.4%), and one softball player (1.4%, a female patient). Of the patients, 34 played at the high school level (46%), 39 played at the college level (53%), and one played at the professional level (1.4%). The injured arm was on the right side in 55 patients (74%) and on the left in 19 patients (26%). MRI scans with and without intra-articular contrast were available for review in 46 of 74 patients (62%) and 28 of 74 patients (38%), respectively.

ICCs of measurements

The ICCs were 0.87 (95% CI, 0.80-0.92) and 0.95 (95% CI, 0.92-0.97) for joint space measurements on static and stress radiographs of the injured elbow, respectively, and 0.95 (95% CI, 0.93-0.97) for joint space measurements on stress radiographs of the uninjured elbow (figure 4.3). These values represented

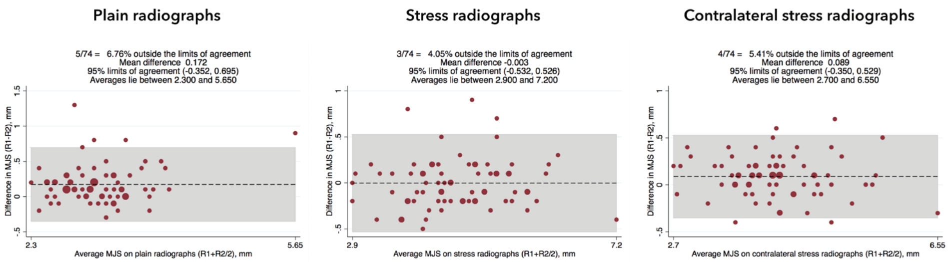


Figure 4.3 Bland-Altman plots of the level of agreement of joint space measurements by rater 1 and rater 2 on plain radiographs (left panel), stress radiographs (middle panel), and contralateral stress radiographs (right panel). The difference between two measurements is depicted on the Y-axis and the average of two measurements is depicted on the X-axis (both in millimeters). The limits of agreement are marked by the gray area around the mean difference (black dotted line).

good to excellent interobserver agreement, and averages of the two independent measurements were used as the final value for each patient.

Medial joint gapping and excess opening

The medial joint space measurements are summarized in table I. The average medial elbow joint space distance of the injured elbows was 3.1 mm (SD, 0.5 mm) without valgus stress and 4.6 mm (SD, 0.8 mm) with valgus stress, resulting in average medial joint gapping with stress of 1.4 mm (SD, 0.7 mm). The average medial elbow space distance of the uninjured elbows with valgus stress was 4.2 mm (SD, 0.7 mm). The average excess opening was 0.4 (SD, 0.6), representing a greater joint opening of the injured elbow than the uninjured elbow with valgus stress ($P < .001$, paired *t* test; 95% CI, 0.3-0.6 mm).

A total of 45 patients (61%) had partial-thickness UCL tears of the anterior bundle, whereas 21 patients (28%) showed full-thickness UCL tears. The remaining seven patients (9%) did not show signs of UCL tearing on MRI (intact UCL). An increase in joint gapping of injured elbows was related to an increase in UCL injury severity ($P = .003$), and group-level comparison of joint gapping showed a borderline-significant difference among individual tear severity groups (intact vs. partial vs. complete, $P = .050$). Post hoc Bonferroni-corrected pair-wise comparison did not reach significance for either of the injury severity groups (figure 4.4A). Subgroup analysis of patients with and without MR arthrograms showed similar findings for the increase in joint gapping of injured elbows in patients regarding overall trends ($P = .022$ and $P = .028$, respectively) but showed no group-level differences ($P = .124$ and $P = .159$, respectively).

The amount of excess opening (uninjured minus injured medial joint space on stress view) was not significantly related to UCL injury severity ($P = .109$), and group-level comparison of excess opening among individual tear severity groups showed no significant differences among groups (intact vs. partial vs. complete, $P = .350$; figure 4.4B). Subgroup analysis of patients with and without MR arthrograms resulted in similar findings ($P = .099$ and $P = .443$, respectively, for overall trends; $P = .407$ and $P = .644$, respectively, for group-level comparison). On stress radiographs, 16 of 74 patients (22%) had a greater medial joint space distance of the uninjured side compared with the injured side, representing a negative excess opening.

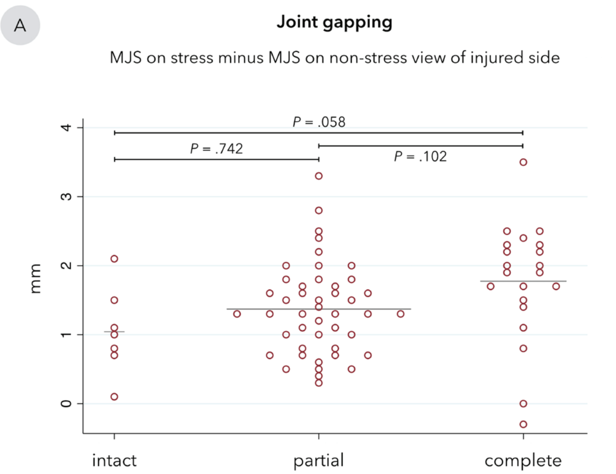
Positive versus negative excess opening

Negative excess opening was observed in 43% of patients with intact UCLs (3 of 7), 18% of patients with partial UCL tears (8 of 45), 19% of patients with complete UCL tears (4 of 21), and one patient with extensive ossification of the anterior bundle. Bivariate comparison of the characteristics of patients with

Table I. Medial joint space measurements on stress and non-stress elbow radiographs.

	mean ± SD (range), mm		
	injured	uninjured	*P* value
non-stress radiograph	3.1 ± 0.5 (2.3 - 5.7)	-	
stress radiograph	4.6 ± 0.8 (2.9 - 7.2)	4.2 ± 0.7 (2.7 - 6.6)	<.001*
stress *minus* non-stress	1.4 ± 0.7 (-0.3 - 3.5)	-	

SD, standard deviation



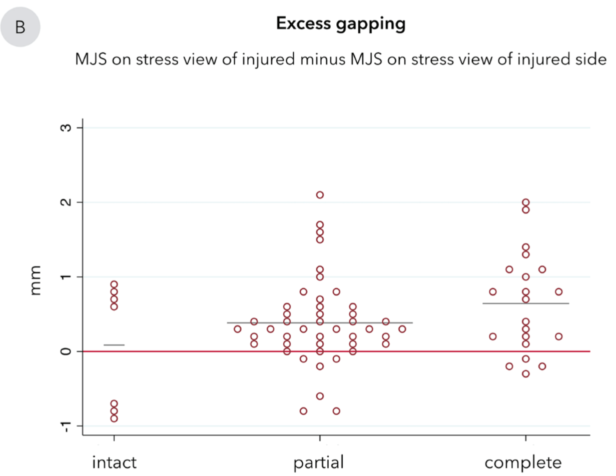


Figure 4.4
Dot plots of
A) joint gapping and
B) excess opening
among patients without UCL tears (intact), those with partial(-thickness), and those with complete (full-thickness) tears.

The *gray* horizontal lines represent group means.

The *pink* horizontal line represents the line of no difference in medial joint space (MJS) between the injured and uninjured elbow on stress radiographs.

Note: one patient with extensive ossification of the anterior bundle was excluded from statistical analysis of joint opening and UCL injury severity.

a positive excess opening and patients with a negative excess opening did not show significant differences in any of the variables corroborating guarding or a mechanical explanation for a decreased medial joint opening of the injured elbow compared with the uninjured elbow (table II).

Discussion

We examined medial elbow joint opening on stress radiographs in seventy-four consecutive throwing athletes with medial elbow pain assessed for instability as part of the standard clinical workup at our clinic to evaluate the usefulness of stress radiography in the management of throwing athletes with a clinical suggestion of UCL injury. Our joint space measurements (static, stress, gapping, and excess opening) were similar to values previously reported in larger samples.[2]

More than two decades ago, Rijke *et al.* (1994) described a method of valgus stress radiography to evaluate throwing athletes with a clinical suggestion of UCL injury.[13] In these athletes, standardized anteroposterior radiographs of the injured and contralateral uninjured elbows were obtained under 0 and 15 daN of valgus force applied with the joint at 25 degrees of flexion, full supination of the forearm, and 65 degrees of abduction of the shoulder. This technique was validated by examining cadaveric elbows with progressive UCL transaction (25%, 50%, 75%, and 100%), in which the authors observed a linear correlation between medial joint gapping and degree of transaction. The results were then compared with intraoperative findings of complete or partial tears of the UCL,

Table II. Positive versus negative excess opening.

Variable	positive excess (n = 58)	negative excess (n = 16)	*P* value
Age, y, mean ± SD	18.9 ± 2.5	18.0 ± 2.1	.203
Symptom duration, wk, mean ± SD	33.7 ± 56.8	23.8 ± 21.7	.508
Physical examination, n (%)			
Limited elbow extension	12 (21)	4 (25)	.737
UCL tenderness	46 (79)	10 (63)	.195
FP tenderness	6 (10)	1 (6.3)	>.999
Pain with MVST *	50 of 57 (88)	10 of 12 (83)	.650
MRI, n (%) **			
FP muscle edema	20 (34)	4 (25)	.558
PMO or loose bodies	15 (26)	5 (31)	>.999

y, years; *SD*, standard deviation; wk, weeks; UCL, ulnar collateral ligament; FP, flexor-pronator; MVST, moving valgus stress test; MRI, magnetic resonance imaging; PMO, posteromedial osteophytes. * MVST findings were not reported in 5 out of 74 patients (6.8%); ** MRI scans with and without intra-articular contrast were available for review in 46 (62%) and 28 out of 74 patients (38%), respectively.

and Rijke *et al.* concluded that standardized stress radiography of the elbow could be used to accurately diagnose the extent of UCL injury. They advocated the use of stress radiography over MRI because of the low cost, fast execution, and ability to dynamically evaluate the functional integrity of the UCL of the elbow (in contrast to static MRI). Although this study was useful 25 years ago, when MRI was not so readily available and imaging techniques were of lower quality, nowadays, 1.5 to 3 T MR arthrography is commonly available, enabling detailed evaluation of ligaments and other important structures of the elbow joint.

Lee *et al.* (1998) observed a significant amount of medial joint opening in the uninjured elbows of non-athlete volunteers.[11] In the same year, Ellenbecker *et al.* reported a greater amount of medial joint opening in the dominant elbow than in the non-dominant elbow in asymptomatic baseball players.[5] This finding was corroborated by Singh *et al.* (2001), observing the same phenomenon in asymptomatic collegiate baseball players.[14] On the basis of these studies, we may conclude that valgus opening occurs in athletes and non-athletes, as well as injured and uninjured individuals, indicating that stress radiography may not be as useful as theorized. Moreover, in accordance with the limitations of stress assessments of the knee, reliable use of this method in the elbow may be challenging.[8,12]

Based on our clinical sample, the amount of joint gapping of injured elbows seemed to be significantly related to UCL injury severity on MRI, but group-level post hoc comparison only showed a trend toward a significant difference in joint gapping between patients without UCL tears and patients with full-thickness tears (1.0 mm vs. 1.8 mm, $P = .058$). Furthermore, our data suggest that excess opening - representing the difference in joint space opening of injured versus uninjured elbows - was not significantly related to UCL injury severity. This latter finding is relevant in light of the original description of the interpretation of stress radiography, in which determination of significant UCL injury is based on contralateral comparison of joint opening.

We observed a negative excess opening in 22% of patients in our sample (16 of 74). This phenomenon has been observed in previous studies, but no evidence-based explanations have been established yet.[2,14] The hypothesis of guarding as an explanation for negative excess opening with stress radiographs may be supported if patients with a negative excess opening more frequently present with acute symptoms, UCL tenderness, pain on the moving valgus stress test, and/or flexor-pronator tenderness or muscle edema on MRI. One alternative hypothesis was that a negative excess opening is the result of a decreased range of motion due to mechanical blocking, caused by possible posterior osteophytes and/or loose bodies. However, we did not observe significant correlations among clinical characteristics in patients with a negative versus positive excess opening, nor did we observe characteristics that corroborated mechanical explanations for a negative excess opening. Therefore, the counterintuitive but common finding of a negative excess opening (22-31%) in throwing athletes undergoing stress radiography remains to be elucidated. The high prevalence of a negative excess opening does suggest a compromised validity of stress radiographs for medial joint opening measurements.

An interesting avenue for future research and an alternative explanation of a negative excess opening observed in throwing athletes may be thickening of the elbow capsule, similar to the thickening of the posterior capsule in the shoulder of throwing athletes, resulting in decreasing shoulder range of motion (i.e., internal rotation). Hypothetically, repetitive loading of the elbow joint with valgus stress leads to chronic thickening of the ligament, which may account for a decreased medial joint opening on stress testing. Baseline anatomic changes to the UCL in dominant elbows of elite-level baseball pitchers have been observed previously with a significantly greater thickness of the UCL of the throwing elbow compared with the UCL of the non-throwing elbow.[4] This phenomenon would also explain the relatively high percentage of patients with intact UCLs on MRI but a negative excess opening with stress testing in our series (3 of 7, 43%).

Limitations

Because static radiographs of uninjured elbows were not included in the standard workup of our patients (avoiding unnecessary radiation exposure), our calculation of an excess opening differs slightly from the calculation previously described by Bruce *et al.*[2] However, there was no significant difference in the medial joint space on static radiographs of injured versus uninjured elbows observed in their large series; therefore, we are confident that our measurements of excess opening are comparable to previous reports. In addition, the forces generated during throwing are much higher than the 15 daN recreated with the Telos stress device, which may result in an underestimation of the actual gapping during throwing. An important additional consideration for the interpretation of our study findings was the use of purely clinical data that were obtained after the performance of stress radiography in patients in a relatively uncontrolled clinical setting. Although technicians instructed patients to only loosely grip the handle of the Telos device, the actual gripping strength was not monitored, which may have led to an increase in tension of the upper extremity, altering valgus stress resistance and limiting joint opening.

Finally, a limitation of this study was that both MR arthrograms and MRI without intra-articular contrast were analyzed. It is known that the sensitivity and specificity for UCL injury severity vary for these two techniques, with MR arthrography possible overestimating tears and plain MRI scans being at risk of underestimating tears. Additional subgroup analysis of the sample of patient with intra-articular contrast and those with plain MRI scans showed similar findings regarding overall threads but loss of significant group-level differences - findings that may be driven by a decrease in sample size.

Conclusion

Medial joint gapping was correlated to UCL injury severity in throwing athletes with medial elbow pain and a clinical suggestion of UCL injury, but no association between UCL injury severity and excess opening (bilateral comparison of medial elbow opening) was observed in our clinical series, possibly limiting the clinical usefulness of stress radiography. It is our perception that, with the current status of MRI as the gold standard for UCL injury, stress radiographs may be of limited use in the workup of throwing athletes with medial elbow pain. In accordance, stress radiographs do not substantially aid decision making in clinical practice, they expose (young) patients to unnecessary radiation, and they add needless costs to the health care system. Future prospective experimental studies are mandatory to verify guarding as a major confounding factor of stress radiography, but this study may fuel the academic discussion for the appropriate and cost-effective evaluation of the UCL in throwers.

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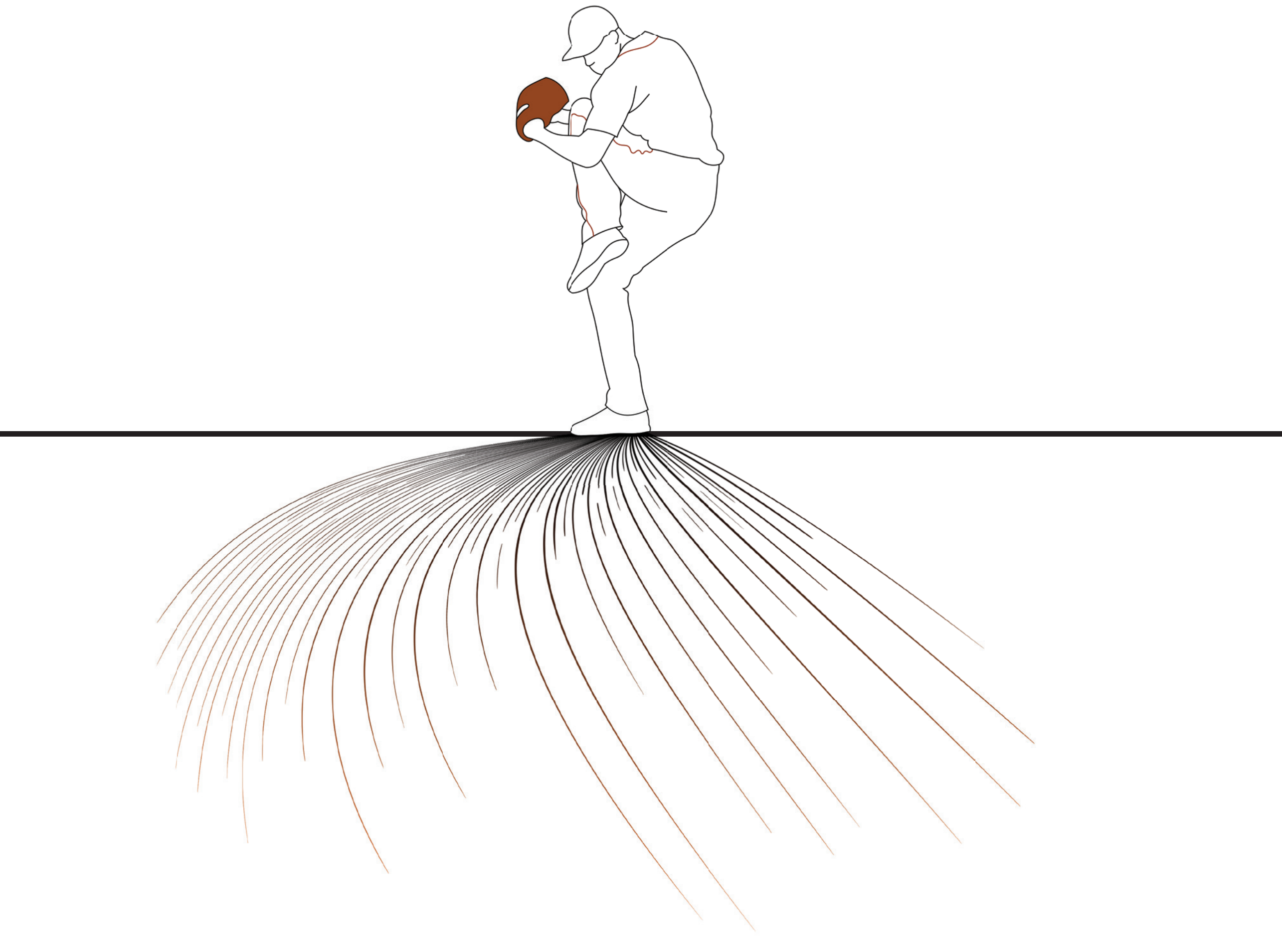
PART III

UCL PATHOANATOMY AND SURGICAL RECONSTRUCTION



5

Pathoanatomy of the anterior bundle of the medial ulnar collateral ligament

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ABSTRACT

Background
The purpose of this study was to increase our understanding of the pathoanatomy of the ulnar collateral ligament (UCL) by performing a descriptive analysis of the surgical inspection of the anterior bundle in patients undergoing reconstruction.

Methods
A single-surgeon series of 163 patients who underwent UCL reconstruction between 2009 and 2017 was retrospectively analyzed. Descriptions of the pathoanatomy of injury were obtained from the operative reports. Magnetic resonance imaging data were reviewed to assess whether the presence and location of tissue disruptions were accurately recognized. Demographic and clinical characteristics were obtained from medical records and correlated to observed pathoanatomy.

Results
Injuries to the anterior bundle were characterized by a single tissue disruption (65%), tissue disruptions at more than one location (23%), or injuries without distinct fiber tissue disruptions (12%). The presence and location of tissue disruptions matched magnetic resonance imaging findings in 124 of 153 patients (81%). Partial tears more frequently affected the anterior band of the anterior bundle distally as opposed to the posterior band of the anterior bundle proximally (P = .012). Patients with single tissue disruptions more frequently reported a popping sensation than patients with non-tear insufficiency (P = .030).

Conclusions
This study shows the heterogeneity of anterior bundle injuries in patients undergoing ulnar collateral ligament reconstruction. A variety of injury configurations and chronic attritional damage to the anterior bundle were observed, as well as distinct tear patterns at the distal and proximal attachment sites. Future research may elucidate the diagnostic value of a pop sign for ulnar collateral ligament injury.

Introduction

Overhead and upper-extremity weight-bearing athletes, such as baseball pitchers, tennis players, and gymnasts, are at an increased risk of medial ulnar collateral ligament (UCL) injury. The UCL is located on the medial side of the elbow and consists of the anterior, posterior, and transverse bundle (figure 5.1). The anterior bundle of the UCL connects the sublime tubercle (ulna) and the anteroinferior part of the medial epicondyle (humerus), serving as the main restraint to valgus and torque forces applied to the elbow.[4,8,10,14] The anterior bundle can be further subdivided into an anterior and posterior band, with different strain patterns through elbow range of motion.[12,23] As tremendous valgus and torque forces are applied to the medial side of the elbow during overhead and weight-bearing athletic activities, the anterior bundle is the UCL's structure at risk of injury in these types of athletes.[2,6,18]

The repetitive valgus stress applied to the medial elbow during baseball pitching, serving in tennis, or upper-extremity weight-bearing may lead to microtrauma to the anterior bundle of the UCL. Over time, this microtrauma is thought to negatively affects the structural integrity of the tissue, leading to ligamentous insufficiency. An acute overload moment may cause rupturing of the worn ligament, which may be felt or heard as a pop. Throwing athletes with significant insufficiency of complete rupture of the anterior bundle of the UCL are

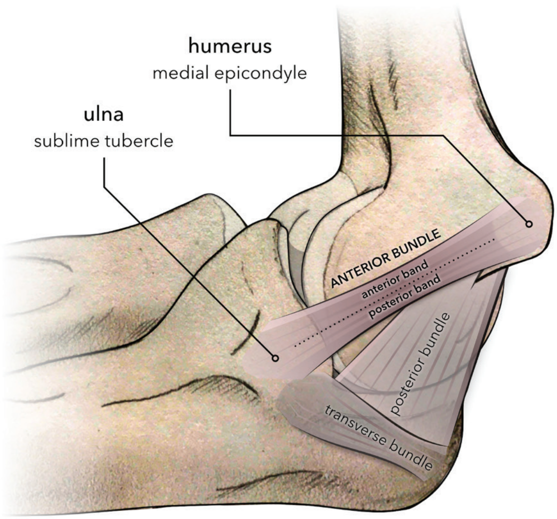

Figure 5.1
Anatomy of the medial ulnar collateral ligament: anterior bundle (connecting anteroinferior medial epicondyle of the humerus and sublime tubercle of the ulna and subdivided into an anterior and posterior band), posterior bundle, and transverse bundle.

typically unable to continue to throw and often require surgical intervention.[13,16] A successful return to sport has been reported in 85 to 95% of patients after UCL reconstruction, but rehabilitation is strenuous and generally requires more than twelve months.[5,15,17,22]

There are indications that the type and location of UCL injury to the anterior bundle are clinically relevant. For example, it has been suggested that distal tears of the anterior bundle may be less amenable to nonoperative management than proximal tears in professional pitchers.[9,10] Furthermore, primary repair of the anterior bundle bundle, rather than reconstruction, may be a viable option in younger athletes with localized or acute distal or proximal tears, as the lower levels of chronic attritional stress may have preserved a better structural integrity of the remainder of the ligament.[19,21]

The main purpose of this study was to increase our understanding of the pathoanatomy of injury to the UCL by performing a descriptive analysis of the surgical inspection of the anterior bundle in a single-surgeon cohort of patients who underwent UCL reconstruction. We hypothesized that UCL injuries would be a heterogeneous entity, manifesting in various configurations of chronic and acute tissue damage. Our secondary goal was to examine the association between demographic and clinical characteristics and the types of pathoanatomy observed during surgery.

Materials & methods

This is a retrospective review of a single surgeon's intraoperative evaluation of 163 anterior bundles of the UCL during surgical reconstruction. The medical records and operative reports of patients undergoing UCL reconstruction from 2009 to 2017 performed by the senior author (LSO) at our institution were analyzed. The multi-institutional Research Patients Data Registry was searched using Current Procedural Terminology codes (24345 and 24246) to collect the data of patients who underwent UCL reconstruction. The senior author performed 176 UCL reconstructions and 163 out of 176 patients (94%) had operative reports containing an explicit description of the observed injury to the anterior bundle of the UCL available for review and were included for analysis. All medical records and operative notes were reviewed and assessed by the first author (RJM) and last author (LSO) using the Electronic Medical Record system (QPID Health, Boston, MA, USA).

During surgery, the flexor pronator muscle mass was elevated from the anterior bundle of the UCL, exposing the ligament for inspection. The undersurface of the anterior bundle was examined after longitudinal incision at the equator of the anterior bundle (between the anterior and posterior bands). Tear descriptions and observations of attenuation, perforation (focal hole within tissue), ossification and calcification, and scar tissue formations, as well as the location and extent of these injury manifestations were obtained from the operative reports.

Demographic characteristics were obtained from the medical records, including sex, age, race, type of sport, level of play, hand dominance, side of injury, cause of injury, onset of injury, occurrence of a pop during the initial injury, time between the initial injury and surgery, history of significant ipsilateral elbow or shoulder injury, and prior arthroscopic removal of posteromedial osteophytes. Available magnetic resonance imaging (MRI) data (1.5 or 3,0 T) were evaluated using the Picture Archiving and Communications system (GE Centricity System workstations, version 2.1; GE Healthcare Systems, Chalfont St. Giles, UK) and reviewed to assess whether the presence and location of tissue disruptions matched the MRI findings.

Statistical analysis

Data were described using frequencies and percentages for dichotomous and categorical variables, means and standard deviations for normally distributed continuous data, and medians and interquartile ranges for nonparametric continuous data. Data comparisons were performed using the Fisher exact test for binary and categorical outcome variables and the Kruskal-Wallis test for nonparametric continuous outcome variables. *P* values were adjusted for multiple comparisons using the false discovery rate correction. Post hoc pair-wise comparisons were performed using the Fisher exact test with Bonferroni correction.[1] Statistical analysis was performed using STATA/SE statistical software (version 14.2; StataCorp, College Station, TX, USA). False discovery rate-adjusted *P* values less than .05 were considered statistically significant.

Results

Demographic characteristics

The demographic characteristics of the patients included in this study are summarized in table I. The study population consisted predominantly of white, male, high school or collegiate baseball pitchers. MRI data were available for review in 153 out of 163 patients (94%), of who 93 patients (61%) underwent magnetic resonance arthrography.

UCL anterior bundle injury

Figure 5.2 shows the breakdown of injury manifestations observed in our sample. The main characteristic of the majority of UCL injuries was a single tissue disruption (106 out of 163 patients, 65%; further distinguished into single tears and single perforations) or tissue disruptions at more than one location of the

Table I. Demographic characteristics (n = 163).

Variable	n	(%)	Variable	n	(%)
Male sex	158	(97)	Sport		
Age, median (IQR), years	19.1	(2.6)	Baseball	152	(93)
Time to surgery, median (IQR), wk	11.7	(18.7)	Pitcher	132	(87)
Race			Catcher	5	(3.3)
White	146	(90)	Other position	15	(9.9)
Hispanic	6	(3.7)	Javelin	5	(3.1)
Asian	4	(2.5)	Softball	2	(1.2)
Other or unknown	7	(4.3)	Gymnastics	2	(1.2)
Hand dominance			Quarterback	1	(0.6)
Left	28	(17)	Snowboarding	1	(0.6)
Right	135	(83)	Level of play		
Cause of injury			High school	66	(40)
Throwing	154	(94)	Collegiate	87	(53)
Hyperextension valgus trauma	5	(3.1)	Professional	9	(5.5)
Other	4	(2.5)	Recreational	1	(0.6)
Onset of injury			History of surgery		
Acute moment	106	(65)	Yes	41	(25)
Non-acute moment	54	(33)	Elbow	37	(90)
Unknown	3	(1.8)	PMO removal	17	(46)
Popping sensation			Shoulder	4	(10)
Yes	48	(29)	No	122	(75)
No	115	(71)			
Unknown	3	(1.5)			

IQR, interquartile range; *PMO*, posteromedial osteophyte

anterior bundle (in 37 out of 163 patients, 23%; further distinguished into tear-and-perforation combinations and multiple tears). The anterior bundles of the remaining twenty patients (12%) did not show distinct fiber tissue disruptions but were characterized by localized or generalized signs of chronic injury, such as attenuation (stretched out or loose with forceps), functionally incompetent and therefore classified as non-tear insufficiency of the anterior bundle.

Table II summarizes the various injury characteristics of the anterior bundle in our study population and among the five subgroups. Tissue disruptions

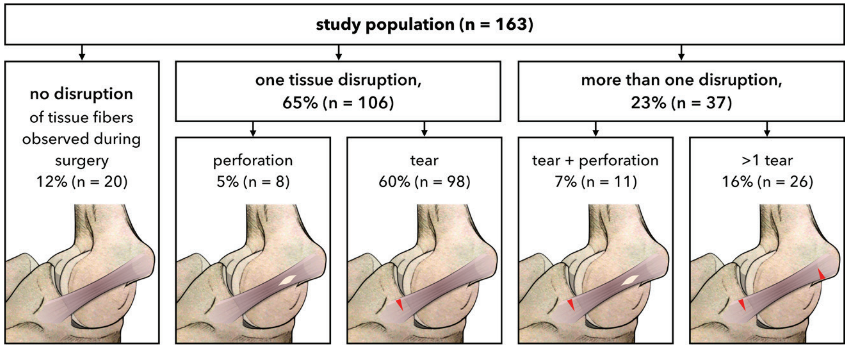

Figure 5.2 Breakdown of study population into five subgroups based on injury configuration.

Table II. Injury characteristics of the anterior bundle in patients undergoing UCL reconstruction.

Variable, n (%)	NT insuff. (n = 20)	perforation (n = 8)	tear (n = 98)	tear + perf. (n = 11)	>1 tear (n = 26)	total (n = 163)
Tissue disruption	0 (0)	8 (100)	98 (100)	11 (100)	26 (100)	143 (88)
Distal	-	0/8	41 (43)	1/11	0	43 (30)
Mid substance	-	2/8	11 (11)	0/11	0	13 (9.1)
Proximal	-	6/8	45 (46)	2/11	0	53 (37)
Distal and proximal	-	-	-	7/11	21 (81)	28 (20)
Other	-	-	-	1/11	5 (19)	6 (4.2)
Scar tissue	3 (15)	1 (13)	38 (39)	0	6 (23)	48 (29)
Generalized	1/3	0/1	3 (11)	-	2/6	7 (15)
At site of disruption	-	0/1	30 (79)	-	0/6	30 (63)
At site of disruption and other location	-	0/1	0	-	4/6	4 (8.3)
At other location than site of disruption	-	1/1	4 (11)	-	0/6	5 (10)
Localized (without tissue disruption)	2/3	-	-	-	-	2 (4.2)
Attenuation	19 (95)	5 (63)	51 (52)	9 (82)	15 (58)	99 (61)
Generalized	10 (53)	-	9 (18)	1/9	4 (27)	24 (24)
At site of disruption	-	3/5	28 (55)	2/9	10 (67)	43 (43)
At site of disruption and other location	-	-	4 (7.8)	5/9	1 (6.7)	10 (10)
At other location than site of disruption	-	2/5	10 (20)	1/9	0	13 (13)
Localized (without tissue disruption)	9 (47)	-	-	-	-	9 (9.1)
Ossifications or calcifications	1 (5.0)	0	10 (10)	0	1 (3.9)	12 (7.4)
Calcifications	0/1	-	3/10	-	0/1	3 (25)
Ossicle or loose body	0/1	-	6/10	-	1/1	7 (58)
Ossification of ligament	1/1	-	1/10	-	0/1	2 (17)

NT insuff, non-tear insufficiency; *perf*, perforation were located at the proximal attachment site, midsubstance, and distal attachment site of the anterior bundle in 37% (53 out of 143 patients), 9.1% (13 out of 143), and 30% (43 out of 143), respectively, and at both the proximal and distal attachment sites in 20% (28 out of 143). Full-thickness perforations of the anterior bundle were observed in nineteen patients, with these perforations being the main injury component in eight patients. In the other eleven cases, both a perforation and a tear of the anterior bundle observed. Among patients with one or more tissue disruptions of the anterior bundle, scar tissue formation at the location of the disruption was observed in 29% of patients (41 out of 143). Of patients with tears and/or perforations, 56% (80 out of 143) showed areas of attenuation and thinning of the anterior bundle; in the majority of these patients, the area of disruption or beyond was affected (67 out of 80, 84%).

The anterior bundles of the subgroup of patients who did not show distinct fiber disruptions were predominantly defined by attenuation and thinning of the anterior bundles (19 out of 20 patients, 95%). Ten of these patients were observed to have attenuation and thinning of the tissue fibers throughout the entire course of the anterior bundle (10 out of 19, 53%).

Calcifications and loose bodies were observed in 6.1% of patients (10 out of 163). In addition, one notable patient showed a complete tear at the midsubstance between two ossified regions of the anterior bundle and one patient showed a nearly completely ossified anterior bundle with only a very small portion of the proximal aspect of the ligament that was not ossified.

Comparison with magnetic resonance imaging

The presence and location of tissue disruptions matched the MRI findings in 124 of 153 patients (81%). A complete match was found in 103 of 153 patients (67%), including 9 patients who appeared to have a UCL tear on MRI that was described as a full-thickness perforation of the anterior bundle during surgical inspection. In 21 of 153 patients (14%), a tear was observed on MRI as well as intraoperatively but additional tissue disruption of the anterior bundle was found during surgical inspection that was not recognized on MRI.

A mismatch between injury on MRI and during surgical inspection was found in 29 of 153 cases (19%). In the large majority of these cases (23 of 153 patients, 15%), a tear was observed on MRI whereas surgical inspection revealed attenuation, thinning, or degeneration rather than distinct fiber disruption.

Description of UCL anterior bundle tears

Table III provides an overview of the intraoperative descriptions of the distal, midsubstance, and proximal tears in our sample. Approximately one in ten patients was observed to have a complete or nearly complete rupture of the

Table III. Description of tears of the anterior bundle of the UCL observed during surgery.

	tear location		
Tear description, n (%) *	**distal (n = 70)**	**midsubstance (n = 15)**	**proximal (n = 73)**
High-grade partial tear	12 (17)	1 (6.7)	13 (18)
Peeled off	3 (4.3)	0	2 (2.7)
Partial avulsion off of bone	9 (13)	0	1 (1.4)
Full-thickness or near FT tear	32 (46)	12 (80)	38 (52)
Crescent full-thickness tear	1 (1.4)	0	1 (1.4)
Periosteal sleeve avulsion-type tear	4 (5.7)	0	0
Complete or near-complete rupture	6 (8.6)	1 (6.7)	8 (11)
Undefined tear	3 (4.3)	1 (6.7)	7 (9.6)
Other	0	0	3 (4.1)

FT, full-thickness. * Data of one patient, showing a complex delaminated rupture involving the proximal, midsubstance, and distal attachment sites, were not included in the table.

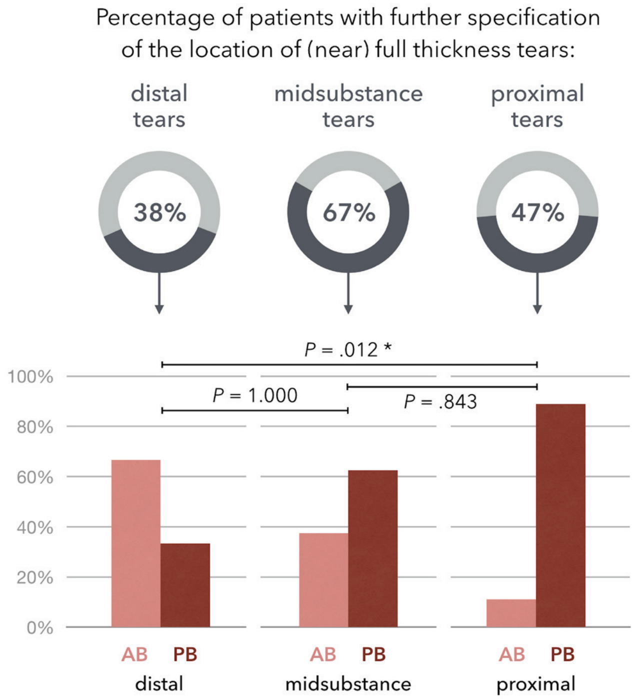

Figure 5.3
Bar charts showing a significant difference in the proportion of anterior band (AB) and posterior band (PB) involvement in distal en proximal full-thickness and near full-thickness tears of the anterior bundle of the UCL.

anterior bundle (9.5%, 15 of 158). In addition, 52% if patients had a tear that was described as a full-thickness or near full-thickness rupture (52%, 82 of 158), indicating complete tissue disruption of part of the anterior bundle. A significant difference in anterior versus posterior band involvement was found among partial tears at the distal versus proximal attachment site of the anterior bundle (*P* = .032). Partial full-thickness tears at the distal attachment site mainly affected the anterior band of the anterior bundle, whereas tears located proximally predominantly involved the posterior band of the anterior bundle (figure 5.3).

Pathoanatomy and patient characteristics

Table IV show the comparison of demographic and clinical characteristics among the subgroups of UCL injuries observed during surgery. The only demographic characteristic that showed a significant difference among the subgroups was the occurrence of a popping sensation at the time of injury (*P* = .032). A pop sign was more frequently experienced by patients with anterior bundle injuries characterized by a single tear compared with patients with non-tear insufficiency (*P* = .030).

Discussion

We examined the pathoanatomy of the anterior bundle of the UCL in a single-surgeon cohort of patients who underwent UCL reconstruction at our institution. We stratified injuries to the anterior bundle of the UCL into five subgroups based on tissue disruption patterns. The observed variety of configurations and signs of chronic attritional injury, including attenuation, scar tissue formation, and ossification, underscores the heterogeneity of injury to the anterior bundle of the UCL. The only characteristic showing a significant difference among the

Table IV. Comparison of demographic and clinical characteristics among subgroups of UCL injuries.

Variable, n (%)	NT insuff. (n = 20)	perforation (n = 8)	tear (n = 98)	tear + perf. (n = 11)	>1 tear (n = 26)	*P* value * (unadj.)
Age, median (IQR), years	18.9 (3.3)	20.0 (2.8)	19.0 (2.2)	20.4 (3.4)	19.2 (2.8)	.532 (.456)
Time to surgery, median (IQR), wk	15.1 (62.8)	17.1 (32.8)	10.9 (23.7)	11.6 (11.0)	12.1 (9.4)	.546 (.546)
Acute moment	9 (47)	4 (50)	69 (71)	8 (73)	16 (64)	.354 (.253)
Popping sensation	1 (5.0)	2 (25)	38 (39)	1 (9.1)	6 (23)	.032 (.009)
Previous shoulder or elbow injury	10 (50)	0	24 (24)	1 (9.1)	6 (23)	.089 (.038)
History of osteophyte removal	5 (25)	0	9 (9.2)	0	3 (12)	.354 (.214)

NT insuff, non-tear insufficiency; *perf*, perforation; *unadj*, unadjusted *P* value; *IQR*, interquartile range; *wk*, weeks.

subgroups was the occurrence of a popping sensation during the initial injury; this was more frequently experienced by patients with isolated single tears than patients with non-tear insufficiency of the anterior bundle (*P* = .030). Furthermore, partial full-thickness tears at the distal attachment site disproportionately affected the anterior band of the anterior bundle, whereas partial tears at the proximal attachment site mainly affected the posterior band (*P* = .012).

The large majority off patient showed one or more tissue disruptions of the anterior bundle of the UCL (143 of 163 patients, 88%), with an evenly balanced prevalence of proximal and distal tears (46% versus 44%). We observed a variety of manifestations of chronic attritional injury to the anterior bundle, including areas of attenuation, scar tissue formation, and calcifications and ossification, subscribing the general assumption that UCL injuries in throwers are etiologically acute-on-chronic injuries.[3,6,7,11,18,20] Distal tears were typically characterized by peeling off or stripping of the undersurface of the anterior bundle from the sublime tubercle. We might speculate that in more severe cases, this avulsion process led to complete detachment of the tissue fibers from the sublime tubercle, resulting in high-grade partial, full-thickness, or complete distal UCL tears. Proximal tears appeared more parallel to the attachment site of the anterior bundle at the medial epicondyle, resulting in more generalized weakening of the proximal tissue fibers (high-grade partial tears) and eventual partial or complete disruption at the proximal attachment site.

Comparison of tear presence and location on MRI shows that what appears to be a tear on MRI may in fact be a perforation of anterior bundle fibers on surgical inspection in a number of cases. Furthermore, what appears to be a low-grade tear on MRI may be an area of attenuation or thinning rather than a distinct fiber disruption. Overall, the presence and localization of tissue disruptions on MRI were found to closely match tissue disruptions as observed during surgery. With increasing quality of MRI, future prospective studies may be able to assess the level of accuracy for detection of more subtle signs of injury to the anterior bundle.

The majority of tears in our sample were partial ruptures defined as full-thickness or near full-thickness tears. Our findings suggest that the anterior band of the anterior bundle is more vulnerable in distal tears, whereas the posterior band is more frequently affected in proximal tears (*P* = .012). This difference may be related to differences in anatomy and strain patterns of the anterior and posterior bands of the anterior bundle through full elbow range of motion. Jackson *et al.* examined the biomechanics of different parts of the UCL and found an isometric strain pattern of the anterior band through elbow range of motion, whereas the strain on the posterior band increased from a level below that of the anterior band at lower flexion angles to a level above that of the anterior band at higher flexion angles (figure 5.4).[12] In addition, Yoshida *et al.* performed an ultrasound study and described significant anatomie differences in inclination angles of the anterior and posterior bands of the anterior bundle at the distal attachment to the sublime tubercle of the ulna, which may be related to the difference in pathoanatomy at the distal and proximal attachment sites observed in our study as well.[23] The exact reasons for the observed difference in anterior band and posterior band involvement in proximal and distal tears remain to be elucidated in future research.

A popping sensation was reported by one-third of patients in our sample, with the highest incidence among patients showing single tears (39%). An interesting finding was that one patient with a non-tear insufficiency injury reported a pop during the initial injury as well. A possible explanation for this finding is that there may have been an acute disruption of more centrally located, encapsulated tissue fibers that could not be observed on the outside of the ligament during direct inspection and was not revealed after longitudinal incision

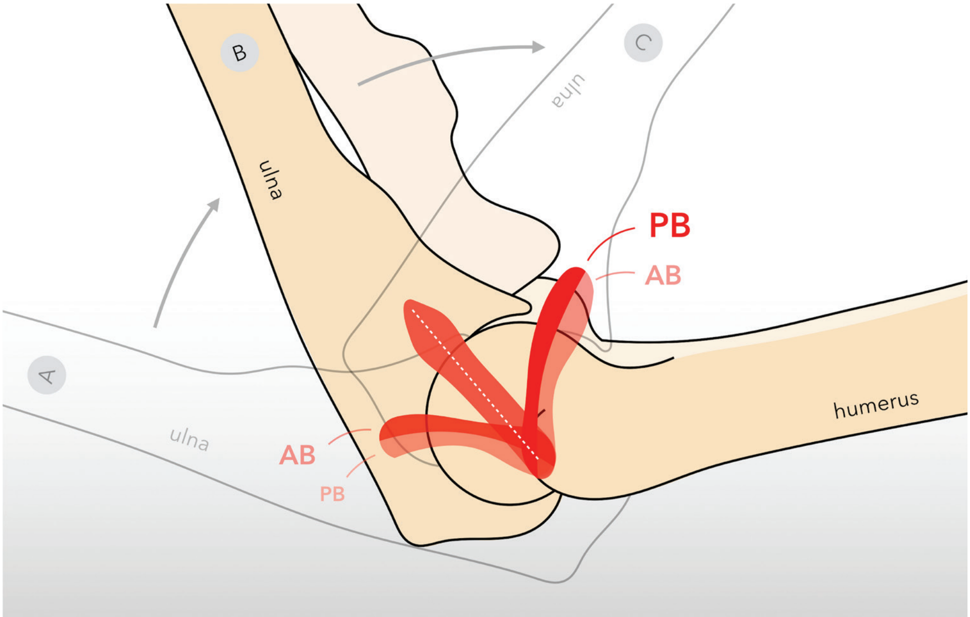

Figure 5.4 Distribution of stress over the anterior bundle of the UCL: With the elbow in extension, tissue fibers of the anterior band (AB) absorb most stress to the anterior bundle of the UCL (A), while the posterior band (PB) absorbs the majority of the stress with elbow flexion (C). Valgus stress is equally distributed to the anterior and posterior band of the anterior bundle with the elbow in approximately 90° of flexion (B).

of the ligament. Future studies may focus on identification of these "covert" fiber disruptions with advanced imaging methods in patients with UCL insufficiency. The popping sensation in patients with UCL injury has not yet been addressed in the current literature, and future studies are needed to elucidate the diagnostic value of the salient finding of a pop sign in patients in whom UCL injury is clinically suspected.

Several limitations must be considered when interpreting our findings. First, the retrospective nature of this study needs to be considered. We analyzed a large single-surgeon series of patients who underwent UCL reconstruction at our institution. Other surgeons may use different terminology or observe other injury details, which may limit the generalizability of our findings. A prospective design with a standard method to characterize UCL injury patterns may improve the accuracy and reliability of similar observations in future research. That being said, the observations by a single experienced surgeon enhanced consistency in terminology, allowing the observation of patterns in the data that are attributable to differences among patients rather than errors related to differences in the use of terminology. Because of the limitations of our retrospective design, future studies are needed to verify the findings of our secondary analyses and provide higher-level evidence for the associations observed. A second limitation is the possible under-reporting of more subtle signs of attritional chronic injury in patients with other more apparent injury to the anterior bundle, such as a complete or extensive full-thickness rupture. Nevertheless, a high prevalence of signs of chronic injury and multifocality of injury was observed in our study. A third limitation is the predominance of throwing athletes in our sample. This limits our findings to throwing-related UCL injuries, which may not reflect the pathoanatomy of valgus-hyperextension UCL injuries in other sports, such as wrestling and judo. However, we believe that our study provides a comprehensive overview of the various appearances of injury to the anterior bundle of the UCL. Considering these limitations, this is the first attempt to describe the pathoanatomy of UCL injury currently available in the literature. An avenue for future research is to further investigate the correlation of preoperatieve imaging to the various manifestations of injury to the anterior bundle of the UCL.

Conclusion

This study shows the heterogeneity of injury to the anterior bundle of the UCL, with the majority of patients showing one or more tissue disruptions of the anterior bundle and a high prevalence of attritional chronic injury. Patients with isolated single tears more frequently experienced a pop sign than patients with non-tear insufficiency injury to the UCL. We observed a difference in anterior band and posterior band involvement in proximal and distal tears, with distal tears more frequently affecting the anterior band and proximal tears more frequently affecting the posterior band. The findings of this study contribute to our understanding of the pathoanatomy of the UCL and may guide sample selections in future research.

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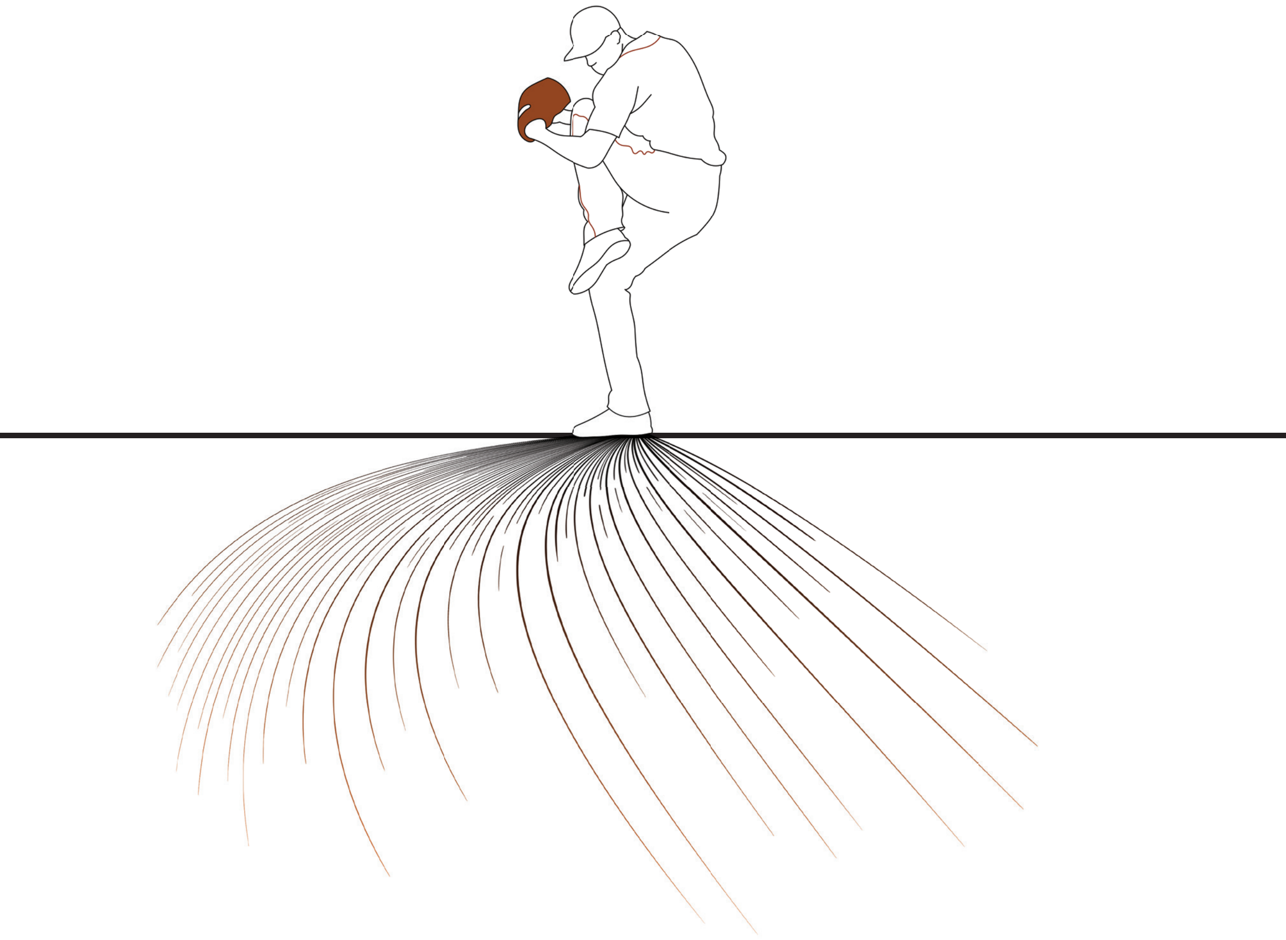

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There is a role for allografts in reconstructive surgery of the elbow and forearm

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ABSTRACT

Purpose
Allografts play an important role in tendon, ligament, and bone reconstruction surgery, particularly when suitable available autologous tissue is limited. Enthusiasm for the use of allografts in reconstructive orthopedic surgery has increased over the past decade, with an increase in allograft use in a variety of procedures. The purpose of this review is to provide an overview of the various applications and indications for the use of allografts in reconstructive surgical procedures of the elbow and forearm.

Methods
MEDLINE/PubMed was searched from 1990 through October 2018 for studies on tendon and bony allografts in elbow and forearm reconstructive surgery.

Results
The Achilles tendon allograft is the most frequently used tendinous allograft, predominantly used in distal biceps and triceps reconstruction. Although reconstruction of the ulnar collateral ligament (UCL) of the elbow is generally performed using autografts, it has been shown that semitendinosus and gracilis grafts may be equally effective. Extensor hallucis longus allografts are recommended for reconstruction of the lateral collateral ligaments in patients with posterolateral rotatory instability, and there may be a role for osteochondral allograft transplantation in capitellar osteochondral defects. In addition, the use of allografts in reconstruction of the interosseous membrane and various bone pathologies (fractures, bone tumors, forearm unions) has been described in current literature.

Conclusion
There is a large variety of pathology and procedures involving the use of various types of allografts in orthopedic reconstructive surgery of the elbow and forearm.

Introduction

Allografts play an important role in tendon, ligament, and bone reconstructive surgery, particularly when suitable available autologous tissue is limited.[1] Advantages of allograft tissue include the lack of donor site morbidity and decreased surgical time compared to autografts.[1] Disadvantages of allografts include the limited availability, higher cost, susceptibility to rejection (due to immune-incompatibility), and potential risk for disease transmission.[1,2] Despite the limitations, enthusiasm for the use of allografts in reconstructive orthopedic surgery has increased over the past decades.[2]

Fresh allografts are transplanted immediately after procurement and include fresh tissue, such as articular cartilage, fresh menisci, or fresh composite grafts.[2] Other allografts are biologic implants, rather than transplants, because of their limited cell viability.[2] These "processed" allografts include a variety of tissues, such as various bone specimens, ligaments, and tendons.[2] Allografts can also be combined with implants, resulting in allograft-prosthesis composites (APC). Because of political and regulatory issues, the availability and costs of allografts vary among European countries.

The purpose of this review is to provide an overview of the various applications and indications for the use of allografts in reconstructive surgical procedures of the elbow and forearm, as well as reviewing the current clinical evidence of the efficacy of allografts in these areas.

Materials & methods

MEDLINE/PubMed was searched using the entry terms "(allograft AND tendon) AND (elbow OR forearm)" and "(allograft AND (bone OR bony)) AND (elbow OR forearm)" from 1990 through October 1, 2018 for studies on tendon and bony allografts in elbow and forearm reconstructive surgery, respectively. This search resulted in 320 hits, which were analyzed for inclusion based on title and abstract by two authors (RJM & JV). All publications focusing on the use of allografts in surgical procedures were included for further analysis. Studies focusing on procedures in regions other than the elbow or forearm were excluded, as well as publications in non-peer reviewed journals. Reference lists of obtained articles were searched for articles relevant to the topic that were not retrieved by the original database search.

Review

Starting in the late 1800s, the first allografts ever used were bone allografts, predominantly in reconstructive tumor surgery. With increasing insights and techniques for preservation and utilization of various tissues, the resources for the use of allografts expanded over the past century. Following the introduction and success of large-bone allografts, soft-tissue allografts – such as the bone-patellar tendon-bone, Achilles tendon, quadriceps, and hamstring tendon allografts – were introduced, and initially used extensively for anterior and posterior cruciate ligament reconstruction in the knee.[2] The following paragraphs synthesize the current literature on the use of soft tissue and bone allografts in orthopedic procedures of the elbow and forearm.

Distal biceps tendon reconstruction

There is a substantial body of literature on the use of allografts in surgical procedures for distal biceps tendons injuries. Distal biceps tendon ruptures most commonly occur in the dominant arm of men in their fifth and sixth decades of life. Surgery is recommended for those with complete distal biceps ruptures.[3,4] Acute primary repair is preferred within 2-3 weeks of injury, as delay can lead to retraction of the biceps tendon due to adhesion formation and loss of elasticity.[4,5] When the biceps tendon has been retracted proximally for a prolonged period, surgical reconstruction using an allograft can be performed.[4,6,7] Alternatively, autografts can be used for this procedure, but the adverse event of donor site morbidity should be considered.

Phadnis *et al.* (2016) described 21 male patients undergoing distal biceps reconstruction using an Achilles tendon allograft for retracted, irreparable distal biceps ruptures.[8] In this prospective study, all patients were satisfied and returned to their previous level of activity with a follow up of 15 months (range, 6-35 months). Similarly, Snir *et al.* (2013) presented the clinical outcomes of 18 patients undergoing distal biceps reconstruction with various allograft tissues, including Achilles tendon (15 patients), semitendinosus (1 patient), gracilis (1 patient), and tibialis anterior (1 patient) for symptomatic chronic ruptures.[9] All patients reported good outcomes after 9 months (range, 4-14 months) and the authors of this study concluded that late reconstruction of chronic ruptures of the distal biceps using allograft tissue was a safe and effective solution for symptomatic patients with functional demands in forearm supination and elbow flexion.

There are various additional case series and reports on the use of Achilles tendon allografts for chronic distal biceps ruptures.[10-14] Both Darlis *et al.* (2006) and Sanchez-Sotelo *et al.* (2002) described good physical function and excellent ratings on the Mayo elbow performance score in 6 out of 7 patients and 4 out of 4 patients with an average follow-up of 2.4 years and 2.8 years.[10,11] Aydin *et al.* (2004) described the successful use of Achilles tendon allografts to reconstruct two-third and three-fourth of the distal biceps after resection of tumoral calcinosis in two patients.[15] In addition to the lower level studies on the use of Achilles tendon allograft, Cross *et al.* (2014) examined the outcomes of 7 patients undergoing distal biceps reconstruction using a tibialis anterior allograft.[16] The early results (16 months follow-up) of distal biceps reconstruction were good to excellent after 16 months follow up as well.

Triceps tendon reconstruction

Triceps tendon injuries can be observed in elbows after a fall on outstretched arm, direct trauma, or with weightlifting. A fourth category is triceps insufficiency in patients with total elbow arthroplasties.[17] Operative repair is indicated for complete triceps tendon tears.[18] When repairs are delayed, soft tissue quality, scarring, and tendon retraction can complicate surgical intervention, requiring reconstruction techniques. One reconstruction technique for chronic triceps insufficiency is the anconeus rotation flap technique, but large tendon gaps or a devitalized anconeus muscle may demand tendon augmentation.

Sanchez-Sotelo & Morrey (2002) described the use of an Achilles tendon allograft with a calcaneal bony attachment in the treatment of 3 patients with triceps insufficiency in the setting of a previous total elbow arthroplasty.[19] They found outcomes similar to anconeus reconstruction, with good subjective results at 38 months follow up. Bennett & Mehlhoff (2015) recently presented their preferred strategies for reconstruction of the triceps tendon with an Achilles tendon allograft.[20] The successful use of hamstring allografts has been described in case reports by Weistroffer *et al.* (2003) and Wolf *et al.* (2008), showing the recovery of two patients with recurrent triceps tendon ruptures.[21,22] Generally, the use of Achilles tendon allografts is preferred over hamstrings grafts for reconstruction of large triceps tendon gaps, as hamstring grafts provide a risk for hamstring weakness and atrophy after graft removal.[18]

Reconstruction of the ulnar collateral ligaments of the elbow

The elbow joint is primarily stabilized by the medial ulnar collateral ligament (UCL) and the lateral collateral ligament (LCL). The etiology of injury varies distinctly between lateral and medial collateral ligamentous injuries. LCL injuries are typically associated with fracture or dislocation of the elbow, whereas UCL injuries are typical overuse injuries observed in overhead athletes.

Severe UCL injuries in overhead athletes require surgical reconstruction to restore valgus stability. In the vast majority of cases, the palmaris longus tendon is used as an autograft.[23] Other options include the use of hamstring autografts, such as the gracilis or semitendinosus tendon. However, a complication rate of 1% related to donor site has been reported.[23,24] Although these complications are generally minor, more severe injuries have resulted from graft harvest, such as median nerve harvest.[25] The use of allografts would eliminate donor site and harvest complications.[26] To this end, Savoie *et al.* (2013) reviewed 116 overhead athletes that were managed with hamstring allografts (100 gracilis, 16 semitendinosus) and found that the use of allograft tissue results in outcomes similar to that of autograft tissue in terms of rate and time to return to sport after 2 years.[27] The authors discuss that their findings oppose concerns on potential delay in healing and inability to withstand high stresses of allografts compared to autografts. Merolla *et al.* (2014) reported similarly good outcomes of UCL reconstruction using semitendinosus allografts in 10 cases.[28]

Opposite to the valgus stability provided by the UCL, the LCL complex is the main component for lateral-sided stability of the elbow and comprises the radial collateral ligament, lateral ulnar collateral ligament, annular ligament, and the accessory LCL.[29,30] Disruption of these structures – for example, by falling on the outstretched hand – can result in posterolateral rotatory instability (PLRI) of the elbow. Non-operative management of chronic PLRI is ineffective and, in general, surgical intervention is required to stabilize the joint.[30] Treatment options include imbrication and repair, as well as reconstruction using an autograft or allograft.[30] Conti Mica *et al.* (2016) recently developed an experience-based treatment algorithm for PLRI, indicating LCL reconstruction using a graft for cases with chronic PLRI, pain, dysfunction, subjective/objective instability, and a dislocating pivot shift test under anesthesia.[30] The authors prefer to perform this procedure using an extensor hallucis longus allograft. In addition to the overview provided by Conti Mica *et al.* (2016), Baghdadi *et al.* (2014) have presented the outcomes of 11 revision LCL reconstructions using plantaris, semitendinosus, and Achilles tendon allografts after failed primary reconstruction.[31]

Capitellar osteochondral defects

Osteochondritis dissecans (OCD) of the humeral capitellum is a rare debilitating and painful disorder most often seen in young, overhead or upper extremity weight-bearing athletes (baseball, gymnastics). Treatment options vary from conservative to surgical management, depending on the severity of injury, especially the extend and stability of the cartilage lesion.[32] Recently, Mirzayan & Lim (2016) were the first to describe the application of fresh osteochondral allograft transplantation (FOCAT) – well reported in the treatment of OCD of the knee – for the treatment of unstable capitellar OCDs.[33] They found good outcomes in 9 baseball pitchers after a mean follow up of 48 months. There are currently no other reports on the application of this allograft technique in the elbow.

Radial head fractures

A traumatic indication for allograft use is in patients with severely comminuted fractures of the radial head. It is preferred to preserve the fractured radial head, but this is not always possible in cases with extensive comminution, as can be observed in fracture-dislocations of the radius, Essex-Lopresti lesions (comminution of the radial head accompanied by dislocation of the distal radio-ulnar joint), or acute longitudinal radio-ulnar dissociation (ALRUD).

There have been various reports on osteochondral allograft transplantation of the radial head. Szabo *et al.* (1997) used a frozen allograft radial head prosthesis and Ilizarov fixation in 5 patients with Essex-Lopresti lesions, resulting in subjective satisfactory outcomes.[34] Karlstad *et al.* (2005) reported on a series of 4 patients with Essex-Lopresti injuries and found failure of 3 out of 5 radial head allografts, with only one patients demonstrating satisfactory elbow function with a useful range of forearm rotation.[35] Turner *et al.* (2012) were the first to report the use of a radial head allograft in the treatment of more complex fracture-dislocations of the elbow, involving fractures of the coronoid and radial head, with collateral ligament disruption.[36] Graft union was confirmed in all 8 patients, with three patients having poor outcomes due to resorption of the coronoid fragment and one patients ultimately undergoing total elbow arthroplasty. Contrary to the previous three reports, Bisicchia & Tudisco (2016) presented the first case involving the successful use of a fresh osteochondral allograft in the acute setting for the treatment of a comminuted fracture of the radial head and neck.[37]

Reconstruction of the interosseous membrane of the forearm

In 1951, Essex-Lopresti described the axial traumatic event of the forearm causing a radial head fracture in combination with a rupture of the interosseous membrane (IOM), causing instability of the distal radial ulnar joint.[38] The rupture of the IOM causes proximalization of the radial head, resulting in a positive ulnar variance, also called acute longitudinal radioulnar dissociation.[39] Because of the low healing capacity of the IOM, reconstruction using either a synthetic graft or allograft is generally required to restore forearm function.[40] There is a paucity of literature on the clinical outcomes of IOM reconstruction using allografts. Current paragraph is therefore limited to biomechanical papers.

Several biomechanical studies are published on IOM reconstruction using allografts. Two studies show that IOM rupture causes increased loading of the radial head that can be resolved using an Achilles tendon or double-bundle flexor carpi radialis allograft reconstruction.[41,42] Tejwani *et al.* (2005) found that a bone-patellar tendon-bone allograft is stronger and tighter than a palmaris longus tendon or flexor carpi radialis tendon, resulting in less proximal migration of the radial head.[43] However, the BPTB allograft is harder to use in clinical practice, because of the fixed length of this allograft.

Revision total elbow arthroplasty

Another category of allograft use is in the field of revision total elbow replacement or total elbow arthroplasty (TEA). Indications for primary TEA are rheumatoid arthritis, osteoarthritis (degenerative joint disease), post-traumatic arthritis, and severe elbow fractures – for instance, in older patients with osteoporosis. Generally, primary TEA is performed using linked or unlinked synthetic implants for the distal humerus and proximal ulna.[44] Complications following TEA include deep periprosthetic infection, ulnar neuropathy, extensor mechanism dysfunction, elbow instability, mechanical failure, and periprosthetic fractures. Periprosthetic fractures frequently demand component revision, including the use of various (bony) allografts.[45,46]

Revision techniques including cortical strut allografts, impaction grafting, and allograft-prosthetic composites (APC) are generally used in periprosthetic fractures with significant bone loss, and high success rates have been reported. For example, Morrey *et al.* (2013) reported on the outcomes of APCs in 25 patients requiring revision TEA due to aseptic implant loosening with a fracture or cortical breach (11), aseptic implant loosening without fracture (3), infection (7), implant failure (1), bone loss after hemiarthroplasty (1), nonunion (1), or resection arthroplasty (1), using three reconstructive strategies (intussusception of the APC, strut-like coaptation, and side-to-side contact between the cortices of the APC and the host bone – see the original aricle for figures of the three reconstructive strategies).[47] The patients in this study showed good functional outcome and a high rate of union, showing the reliability and safety of APCs for revision TEA. Various other retrospective studies subscribe the use of APCs as a reasonable alternative in salvage situations involving TEA with massive bone loss.[48-51]

Impaction grafting for revision TEA has been described by Rhee *et al.* (2013), using iliac crest allograft tissue in the treatment of patients with aseptic loosening of primary implant components with bone loss.[52] Similarly, Loebenberg *et al.* (2005) reported the reliability of impaction grafting in the treatment of osteolysis in patients undergoing revision TEA, including five patients treated with additional allograft struts to span structural defects.[53] In addition, based on their findings in a retrospective study, Kamineni & Morrey (2004) state that most deficiencies of proximal ulnar bone stock and fractures complicating revision TEA can be treated with allograft strut grafting; a technique suitable for discrete cortical lesions, periprosthetic fractures, and extension of the proximal part of the ulna.[46]

Lastly, Foruria *et al.* (2011) reported on the outcomes of 30 patients with periprosthetic fractures around the ulnar stem after arthroplasty requiring revision of the ulnar component using cortical strut allografts.[54] The strut allografts used in this study included 7 femoral, 3 ulnar, 5 fibular, 4 humeral, and one rib cortical struts. Additional impaction grafting was used to restore insufficient cortical bone in expanded ulnae in 8 of the strut graft fixed fractures.

Interposition arthroplasty of the elbow

TEA is successful in older, lower demand patients but not in the younger, more active individual with severe elbow arthritis. Interposition arthroplasty is an alternative for younger patients who hope to minimize the degree to which arm use is restricted, with a variety of interposition materials being described (e.g., autologous fascia lata, bovine collagen, AlloDerm, silicone, and Achilles autografts). In the current literature, there are four studies describing the use of Achilles tendon allografts to perform interposition arthroplasty.[55-58] Larson & Morrey (2008) assessed the outcomes of 38 elbows treated with Achilles tendon autograft interposition arthroplasty with a mean follow-up of 6 years, showing moderate results with 11 out of 38 patients having 'poor' outcomes.[56] The same authors reported on the moderate outcomes of revision interposition arthroplasty using an Achilles tendon autograft in a smaller series of 7 patients.[55] In contrast, in two small case series by Erşen *et al.* (2014) and Chauhan *et al.* (2015), good results of Achilles tendon interposition arthroplasty were shown with a follow up of 7 and 3.6 years, respectively.[57] In conclusion, interposition is a salvage procedure appearing to have moderate to good long term functional results, indicated for patients that are not suitable for TEA. Achilles tendon allografts can be used to protect the joint space in the long-term.

Bone tumors of the elbow and forearm

Due to advanced imaging and the effectiveness of chemotherapy, limb-salvage surgery is the preferred method of management for bone sarcoma.[59,60] Reconstructive options range from allograft transplantation to endoprosthetic reconstruction (or a combination of both). Bone allograft reconstruction can restore bone stock and joint kinematics, while sparing the opposing articular surface.[59] In elbow and forearm literature, the use of osteoarticular, intercalary, allograft arthrodesis, and APCs have been described in various studies.[61-70] The various tumor types described in these studies for the use of various allografts are outside the scope of this review.

Nonunions of the forearm

There are various studies reporting on the use of allografts in patients with forearm nonunions. The most widely adopted treatment for nonunions is surgical repair, stable fixation (frequently with plates), and use of a bone graft, aiming to achieve both mechanical stability and biological stimulation of the bone. Di

Gennaro *et al.* (2017) described the largest series of pediatric post-traumatic forearm nonunions, treated with either Kirschner wires, plates, rush rods, and unilateral external fixator.[71] A strut bone allograft was used in 2 of 12 patients, without complications. Furthermore, Davis *et al.* (2016) recently reported the results of a series of 7 patients with infected forearm nonunions treated using a staged reconstruction technique, consisting of serial debridement, implantation of antibiotic cement spacer, and staged reconstruction using a bulk radius or ulna allograft with intramedullary fixation.[72] Faldini *et al.* (2015) reported no differences in rate of healing between autografts and allografts in the treatment of 34 adult forearm nonunions undergoing a procedure involving either a fibular autograft (20) or allograft bone strut (14).[73] These results were similar to a comparative study by Piotrowski *et al.* (2008), showing no significant differences in the effectiveness and time of bone union between recipients of autogenous or homogenous grafts.[74]

Conclusion

There is a large variety of pathology and procedures involving the use of various types of allografts in orthopedic reconstructive surgery of the elbow and forearm. The Achilles tendon is frequently used in distal biceps and triceps reconstruction, semitendinosus and gracilis allografts have been shown to be effective in UCL reconstruction, and extensor hallucis longus allografts are recommended for reconstruction of the LCL in patients with PLRI. Furthermore, there may be a role for osteochondral allograft transplantation in young athletes with capitellar OCD and biomechanical studies have assessed the effectiveness of allograft tissue to reconstruct IOM ruptures. Finally, the application of APCs in revision TEA, Achilles tendon allografts in interposition arthroplasty, and bone allografts in tumor resection surgery and nonunions of the forearm have been described.

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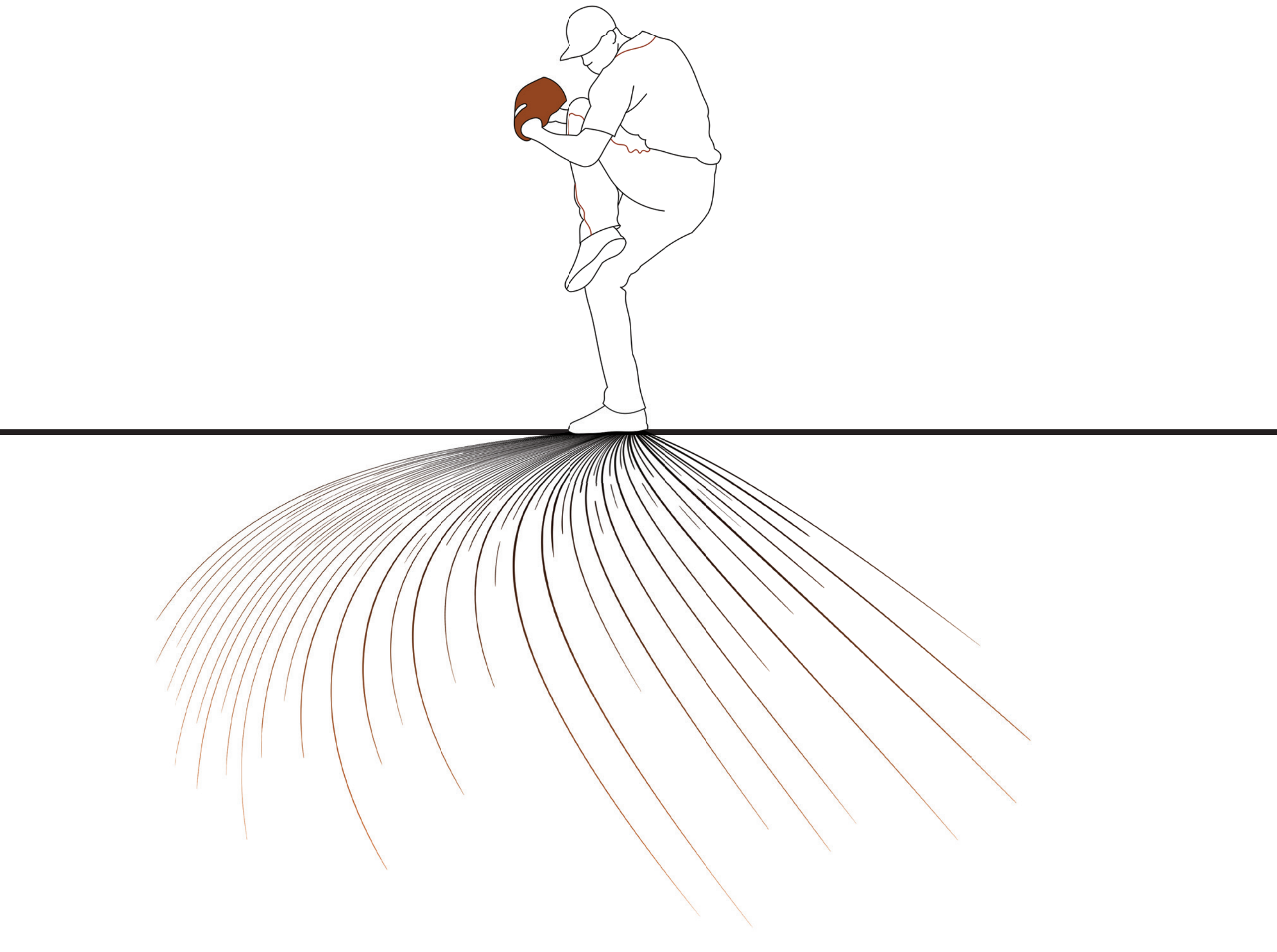

7

General discussion

GENERAL DISCUSSION

BACKGROUND AND AIM

UCL injuries are of primary (medical) concern in throwing sports cultures, such as the United States and Japan. In these countries, every major city has a billion-dollar professional baseball organization, with satellite clubs spread across states and prefectures, and hundreds of thousands of children aspiring for a professional baseball career. The popularity of baseball and corresponding financial interests in effective treatment and prevention of UCL injury have led to a vast literature on UCL injury in baseball pitchers, predominantly from US sources. Despite all efforts, the incidence of UCL surgery has continued to rise over the past decades, especially among younger age groups. This thesis primarily centers on UCL injuries in overhead athletes, with a particular emphasis on those that result from repetitive stress rather than traumatic incidents, as observed in judo, wrestling, and weightlifting, among other sports.

As baseball is more of a niche sport in Europe, UCL injuries are far less common and less well-known among healthcare providers in the athletic field in The Netherlands. This thesis aims to explore what we can learn from established baseball/UCL science and how we can employ those insights in non-baseball overhead athletic disciplines and the Dutch sports context. The data presented in the previous chapters originate from US baseball pitchers and focus on aspects of history taking (Chapter 3), imaging (Chapter 4), and surgical inspection (Chapter 5) of UCL injuries.

The first part of this chapter outlines the current clinical approach to overhead athletes presenting with medial elbow pain and discusses the implications of the studies comprising this thesis. The second part of this chapter highlights established risk factors for UCL injury, raises several critical questions on preventing elbow injuries, and touches upon emerging concepts in technique training and motor control. In the third part of this chapter, the role of UCL injuries in tennis – the number one overhead sport in The Netherlands (~600.000 members) – will be discussed. The final section of this discussion proposes main avenues for future research.

CLINICAL APPROACH TO THE OVERHEAD ATHLETE WITH MEDIAL ELBOW PAIN

A detailed history and physical examination of the elbow are vital parts of the evaluation of an overhead athlete presenting with medial elbow pain. The superficial nature of many elbow structures allows the examiner to collect valuable information from the physical examination. Subsequently, several imaging modalities may help establish the final diagnosis of UCL injury. Depending on the severity of the UCL injury and the athletic demands, treatment options range from conservative management to surgical intervention. The history, physical examination, imaging, and treatment of UCL injury, and the implications of the findings of our studies are discussed in more detail below.

History taking

Onset and duration of symptoms

The evaluation of the athlete with medial elbow pain starts with a detailed throwing history, including the onset and duration of symptoms. Approximately half of throwing athletes with UCL injury present with acute medial elbow pain and inability to compete, while the other half present with more chronic or subtle elbow symptoms, such as decreased command and pitching velocity.[1,2] It should be noted whether the athlete has experienced medial elbow symptoms before (e.g., repeated or continuous episodes of medial elbow pain) or underwent prior conservative or operative treatment (e.g., for flexor-pronator tendinopathy or ulnar neuritis).

Acute UCL injuries may be accompanied by the hearing or feeling of a 'pop' or snap originating from the medial elbow. These events are often of great concern to the athlete and a salient anamnestic finding. The relevance of hearing or feeling a pop in the likelihood of UCL injury was examined in a retrospective clinical cohort of 207 consecutive patients with throwing-related medial elbow pain presenting at the MHG Sports Medicine Center in Boston, US (Chapter 3). An anamnestic popping sensation at the time of injury was reported in 26% of patients and significantly related to UCL injury severity on MR imaging. In contrast to clinical intuition, the occurrence of a pop only moderately increased the likelihood of significant UCL injury, and the absence of a pop did not substantially decrease the likelihood of significant UCL injury.[3] This is in contrast to anterior cruciate ligament injury of the knee, where the feeling of a pop does, in fact, substantially increase the likelihood of injury.[4]

Another essential element in history taking is the phase of the throwing motion associated with elbow pain. High-level overhead athletes are usually aware of the distinct phases of the overhead or throwing motion and the relationship

PRACTICE PEARL

Although often of great concern to the throwing athlete, the feeling or hearing of a pop at the onset of medial elbow pain only moderately increases the likelihood of significant UCL injury, whereas the absence of a pop should not substantially decrease clinical suspicion.

to their complaints. These details help distinguish various elbow pathologies.* The majority of athletes with medial elbow instability (box 7.1) experience pain during the late cocking and acceleration phase of throwing, when valgus peak valgus torques are generated, and tensile forces on the UCL are the greatest.[5] In contrast, pain during deceleration (after ball release) is typically associated with posterior elbow pathologies, such as posteromedial impingement, olecranon osteophyte formation, and loose bodies.[6] Because of their association with UCL insufficiency, UCL evaluation is also warranted in throwing athletes with posterior or lateral elbow pain (valgus extension overload and radiocapitellar osteochondritis dissecans, respectively).

Secondary symptoms

Athletes with UCL injuries may experience secondary symptoms during or in conjunction with throwing. Cold intolerance, along with numbness or tingling in the hand or fingers (typically affecting the fourth and fifth digits, corresponding to the sensory innervation of the ulnar nerve), shooting pain radiating in the forearm, and diminished grip strength, can be an early indicator of neuropathology.[7] Nerve entrapment or peripheral neuropathy may present as a dull, aching pain, while loss of motor control of the hand often represents more severe nerve injury. UCL insufficiency may be the underlying cause of symptoms in patients with failing management or recurrent symptoms of flexor-pronator tendinopathy or ulnar neuropathy.[8] Clinicians should be attuned to the subtle nuances that distinguish flexor-pronator tendinopathy and UCL insufficiency, recognizing that the misdiagnosis of flexor-pronator tendinopathy when UCL injury is the true culprit can result in suboptimal patient outcomes and delay appropriate intervention, impacting both conservative and surgical management strategies.

* The differential diagnosis of pain on the medial side of the elbow includes UCL insufficiency/tear, medial epicondylitis, ulnar neuritis/nerve instability, flexor-pronator tendinopathy, snapping triceps, olecranon stress fracture, and avulsion fracture of the medial epicondyle (in skeletally immature patients).

BOX 7.1 MEDIAL ELBOW INSTABILITY VERSUS LAXITY

Although widely used in UCL literature, it is debatable whether or not the term medial elbow 'instability' is accurate. In other areas of the body, the term instability suggests (sub)luxation of a joint (e.g., of the lateral elbow, shoulder, and knee (related to anterior cruciate ligament injury)). Laxity of the UCL increases medial joint opening without (sub) luxating the elbow joint.

Adaptive laxity is a condition where the body adjusts to increased demands or stress on the joint by allowing for more movement, usually requiring attenuation or elongation of static stabilizers (i.e., ligaments). Adaptive laxity can occur in athletes who engage in repetitive activities, leading to a gradual increase in joint laxity as the body tries to accommodate the specific demands placed on the elbow. Adaptive laxity of the UCL is commonly seen in asymptomatic baseball pitchers.

Traumatic laxity results from a traumatic event, such as a blocked throw in water polo or a hyperextension-valgus moment during an arm-lock in judo or wrestling. The traumatic force can damage the structures that support the elbow joint, including the UCL, leading to abnormal movement and laxity.

On the other hand, **chronic laxity** is a long-standing and persistent instability that may result from genetics and lead to generalized joint hypermobility. Chronic laxity is not a response to external stress but a preexisting condition that may predispose individuals to ongoing joint instability and subsequent vulnarability for musculoskeletal injury.

Prior injuries and the kinetic chain

Clinicians should ask about prior injuries and treatment of the throwing extremity (shoulder, elbow) and the other elements of the kinetic chain (back/trunk, hip, knee, and ankle). The importance of the kinetic chain for effective throwing – with proximal to distal muscle activation and peak torque/force development from the legs and trunk to the elbow – has been extensively analyzed and offers an explanation for the relationship between more proximal injuries (including the shoulder) and functional changes that alter elbow kinematics and risk of injury at the distal kinetic chain.[9,10,11]

Level of competition

A final consideration that needs to be addressed during history taking of the overhead athlete is the level of competition and the temporal aspect of the athletic season. UCL injuries in patients at the amateur or recreational level usually do not require the same aggressive treatment as UCL injuries in professional athletes. Various treatment options exist depending on the severity of UCL injury, and the final decision often depends on the athlete's short-term and long-term professional goals. About the temporal aspect of the season, it is also worth noting that medial elbow pain during preseason or spring training is commonly attributable to flexor-pronator tendinopathy, while UCL injuries predominantly occur in the middle or end of the season.[2]

Physical examination

A thorough physical examination in overhead athletes with medial elbow pain often allows the clinician to diagnose the underlying pathology properly. Diagnostic maneuvers should be performed on the injured and uninjured upper extremity, allowing for bilateral comparison and the assessment of adaptive changes (box 7.2) and overt pathology.[12-16]

Inspection

The thrower's elbow should be examined for soft tissue swelling or ecchymosis (typically along the medial elbow and proximal forearm), which develops within 24 to 72 hours after an acute UCL injury.[13] Athletes with chronic UCL insufficiency usually present with a relatively normal soft-tissue envelope.[17] The carrying angle of the elbow moves from valgus to varus as it moves from extension to flexion. The carrying angle in full extension is approximately 10 degrees for males and 13 degrees for females (figure 7.1).[13,18] A decreased carrying angle on X-ray has been observed retrospectively in patients with elbow pathology, including UCL injuries and radiocapitellar osteochondritis dissecans.[19]

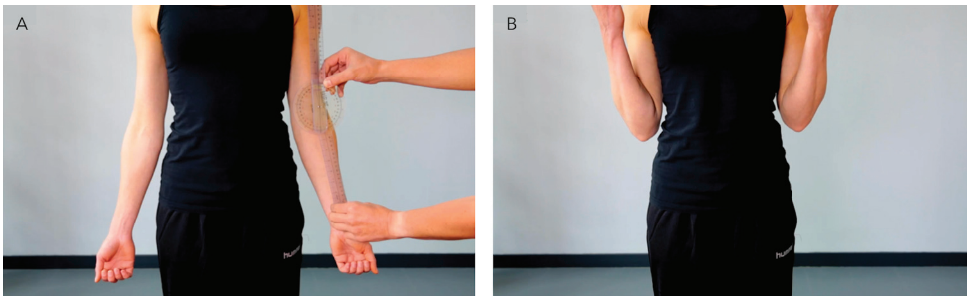

Figure 7.1 The carrying angle of the arm moves from valgus (A) to varus (B) as the elbow moves from extension to flexion.

BOX 7.2
PHYSIOLOGICAL ADAPTATIONS OF THE THROWING ARM

The shoulder and elbow are exposed to tremendous forces during forceful overhead throwing. The human body adapts to repetitive loading in various ways, and the overhead athletes' throwing arm can develop notable changes. Whether these anatomical adaptations should be deemed physiological changes or precursors of pathology is up for discussion. However, clinicians treating elite overhead athletes must be aware of some common adaptations to throwing that occur in the thrower's body and can be observed during physical examination.

General adaptations:

- Unilateral muscular hypertrophy.

Adaptations of the thrower's shoulder:

- Enhanced internal rotation strength.
- Postural scapular asymmetry: internal rotation, anterior tilting, and protraction.
- Increased humeral retroversion due to a more posterior orientation of the humeral head relative to the mediolateral axis of the distal humerus); hypothesized to result from a net retrotorting effect while throwing in the skeletally immature athlete.
- Increased shoulder external rotation arc with concomitant decrease in internal rotation (compared to the contralateral extremity).

Adaptations of the thrower's elbow:

- Carrying angle larger than 15 degrees and 10-15 degrees larger than the contralateral extremity.
- Loss of elbow extension in the throwing arm; traditionally only considered pathological if painful.

King 1969; Dines *et al*. 2021; Astolfi *et al*. 2015; Greenberg *et al*. 2015; Whiteley *et al*. 2012

Palpation

The thrower's elbow's soft spot or 'anconeus triangle' should be palpated to assess for joint effusion. Without joint effusion, this is also the location where a symptomatic synovial plica can be found.[20] The UCL can be accessed directly with the elbow in 50-70 degrees of flexion (in this position, the flexor-pronator muscle mass is transposed anteriorly from the UCL) and should be palpated along the entire course of the anterior bundle. Athletes with UCL injury generally present with point tenderness 2 centimeter distal to the medial epicondyle (sensitivity, 81-94%; specificity, 22%; figure 7.2).[21] Palpation of the flexor-pronator muscle mass is performed by moving distally and slightly anterior to the medial epicondyle.[13] However, differentiation between medial epicondylitis, UCL tears, or apophysitis of the medial epicondyle ("Little league elbow") is often tricky by palpation alone, and additional testing for the competence and function of the UCL is needed to distinguish between these pathological conditions.

Finally, evaluation of the ulnar nerve should be performed in throwing athletes who complain of tingling, numbness, or paresthesia of the fourth and fifth digits. The ulnar nerve can be palpated throughout its course – proximal to the medial epicondyle, through the cubital tunnel, and distally into the flexor carpi ulnaris – and is painful in overhead athletes with traction or compression ulnar neuropathy (figure 7.3). Ulnar nerve instability or subluxation can be assessed by gentle pressure to the ulnar nerve directly proximal to the medial epicondyle while taking the elbow through its flexion-extension arc.[13] Dislocation of the ulnar nerve anteriorly to the medial epicondyle when the elbow is moved from extension into flexion indicates moderate to severe ulnar nerve instability and can cause significant discomfort.[22,23] However, asymptomatic subluxations of the ulnar nerve are common.

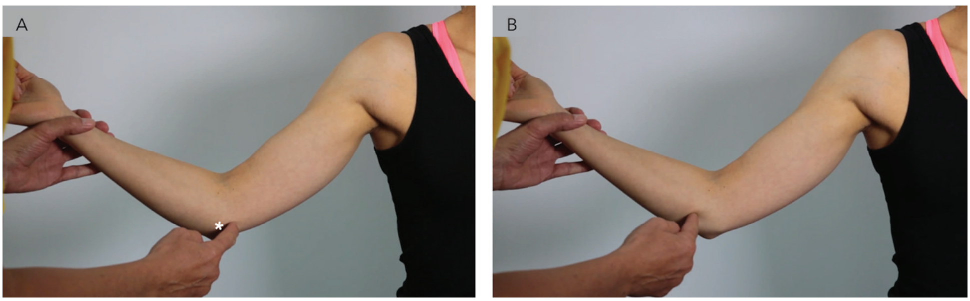

Figure 7.2 A) medial epicondyle (index finger) and ulnar collateral ligament (white asterisk); point tenderness 2 cm distal to the medial epicondyle may indicate UCL injury; B) common flexor tendon.

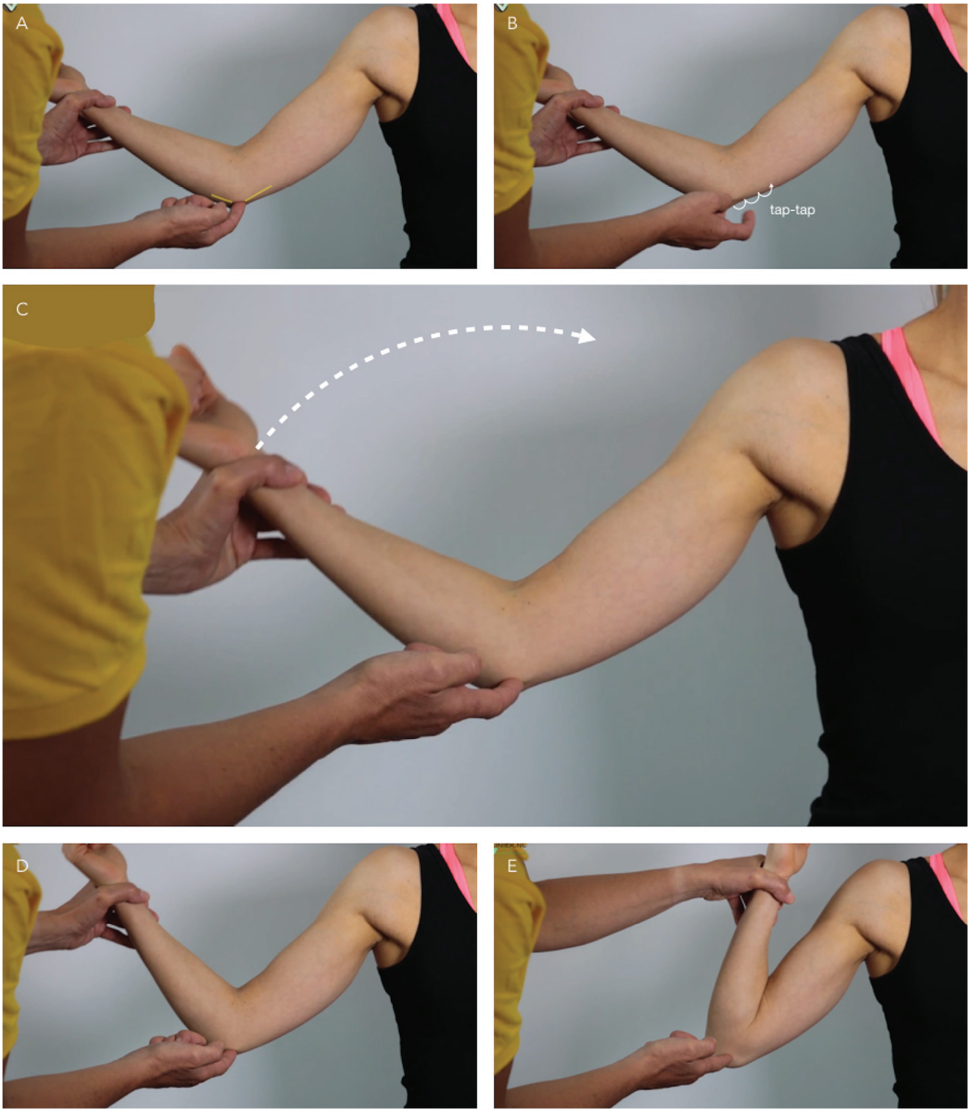

Figure 7.3 Evaluation of the ulnar nerve.

A) Ulnar nerve trajectory (yellow line);

B) Tinel sign - evaluate for provocation of numbness and tingling of the fourth and fifth finger by tapping on the ulnar nerve along its trajectory;

C) Assess for ulnar nerve instability or subluxation by moving the elbow through its flexion arc. A snap at 70-90 degrees of flexion typically represents ulnar nerve subluxation (D), while a snap at 110-120 degrees of flexion is more likely due to a snapping triceps (E).

Range of motion

Normal elbow range of motion is 0 degrees of extension to 140-150 degrees of flexion (figure 7.4), 85 degrees of pronation, and 90 degrees of supination.[24] These ranges of motion slightly vary among males and females and decrease with age. The normal terminal extension generates a bony stop as the olecranon locks into the olecranon fossa. Conversely, terminal flexion typically results in a soft end feel due to the approximation of the biceps brachii and flexor-pronator muscle mass. Forearm pronation and supination typically elicit a capsular end feel. The throwing elbow's active and passive range of motion should be compared to the contralateral elbow as variations in the range of motion or end feel may indicate pathology associated with UCL insufficiency, such as osteophyte formation at the proximal olecranon.[13] Distinguishing between physiological and pathological adaptations of the throwing arm in response to throwing, resulting in asymmetries, provides a diagnostic conundrum (see *box 7.2,* page 124).

Functional tests

The functional integrity of the UCL is assessed with three specific tests: the valgus stress test, milking maneuver, and moving valgus stress test. The valgus stress test is conducted with the patient in a standing position. The examiner externally rotates and fixates the humerus proximal to the elbow joint. The UCL can be palpated just below the medial epicondyle in this position. The other hand fixates the forearm proximal to the wrist joint with the elbow in 20 to 30 degrees of flexion. Subsequently, an abduction or valgus force is applied. A positive valgus stress test is defined as increased laxity (compared to the contralateral side) and pain. It should be noted that valgus laxity is subtle, and valgus stress only increases medial elbow opening by 1 to 2 mm compared to the uninjured elbow in athletes with UCL laxity.[25-27]

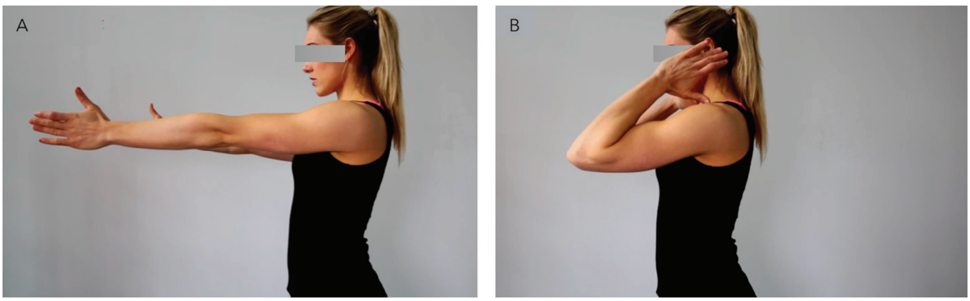

Figure 7.4 Bilateral assessment of normal elbow range of motion: A) terminal extension generating a bony stop at approximately 0 degrees; B) terminal flexion.

To perform the original milking maneuver, the patient is asked to flex the throwing elbow beyond 90 degrees and pull the ipsilateral thumb by reaching under the humerus with the other arm. This position produces valgus stress on the UCL – theoretically isolating the posterior band of the anterior bundle. The examiner should palpate the UCL to assess tenderness and joint space opening. Note that at an angle greater than 120 degrees of flexion, elbow stability is increasingly provided by the bony components of the elbow, decreasing the sensitivity of the milking maneuver in hyperflexion.[13] Modifications of the milking maneuver have been described to eliminate this confounding factor. In the modified milking maneuver described by Safran and colleagues (2004), the throwing shoulder is abducted and externally rotated while the examiner holds the throwing elbow in 70 degrees of flexion by pulling the patient's thumb. This position puts the patient's shoulder in maximum external rotation and generates valgus stress on the UCL. Again, the examiner palpates the UCL to assess tenderness and joint gapping (figure 7.5).[28]

Compared to the valgus stress test and milking maneuver, the moving valgus stress test more closely resembles the shearing forces or 'creep cycle' that the UCL is subject to during the late cocking and early acceleration phase of forceful throwing. The throwing shoulder is abducted and externally rotated. At the same time, the examiner takes the athlete's elbow through its flexion-extension arc under valgus pressure (note that this test position is similar to the position of the modified milking maneuver).[13,28] The moving valgus stress test typically reproduces pain at a specific location within 80-120 degrees of elbow flexion in athletes with UCL injury. A positive test result in athletes with UCL insufficiency may depend on the injury acuity, as patients who had substantial rest before the examination (i.e., have not been throwing for weeks) may produce false negative findings.[13]

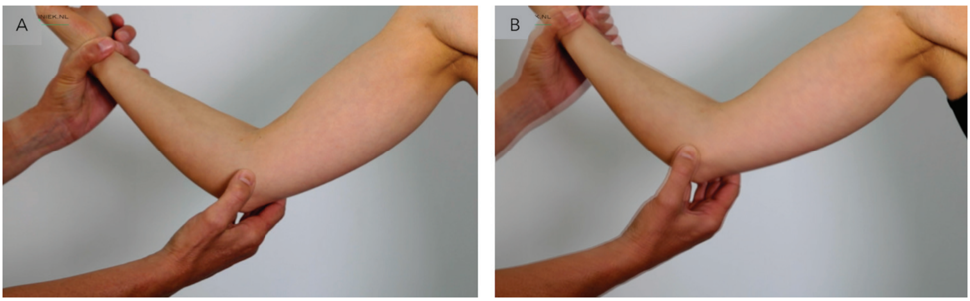

Figure 7.5 Modified milking maneuver: A) Start with the elbow in 70 degrees of flexion, forearm supination, and maximum shoulder external rotation; B) Exert valgus stress on the elbow while palpating the medial joint line for gapping.

In addition to these three tests, the valgus extension overload (VEO) test may indicate the presence of posteromedial osteophyte formation or olecranon fossa overgrowth in athletes with posterior elbow pain (figure 7.6). As this condition is associated with UCL insufficiency, the VEO test is integrated into the overhead athlete's standard examination. The starting position is similar to the starting position of the valgus stress test, fixating the humerus and forearm and quickly bringing the elbow from 30 degrees of flexion to full extension while applying a valgus force to the medial elbow. A positive VEO test produces pain in the posteromedial compartment of the elbow and indicates valgus extension overload syndrome; the absence of posteromedial osteophytes may still render a positive test result (false-positive for posteromedial osteophytes).[29]

Kinetic chain evaluation

The additional assessment of the proximal parts of the kinetic chain is imperative to the complete examination of overhead athletes with elbow pain, especially when patients report complaints or previous injuries in areas other than the elbow. The standard examination of the thrower's elbow should – at a minimum – include a kinematic assessment of the ipsilateral shoulder and scapula, as pathologic glenohumeral internal rotation deficit (GIRD) is associated with UCL insufficiency in baseball players.[30]

As highlighted in the introduction of this thesis, alterations in the kinematics of proximal parts of the kinetic chain have consequences for the load distribution and coordination of distal parts of the kinetic chain. They may be the underlying cause of elbow overload and the development of UCL injury. Recognizing and addressing these impairments could play a vital role in the primary prevention of UCL injury, conservative management of athletes with

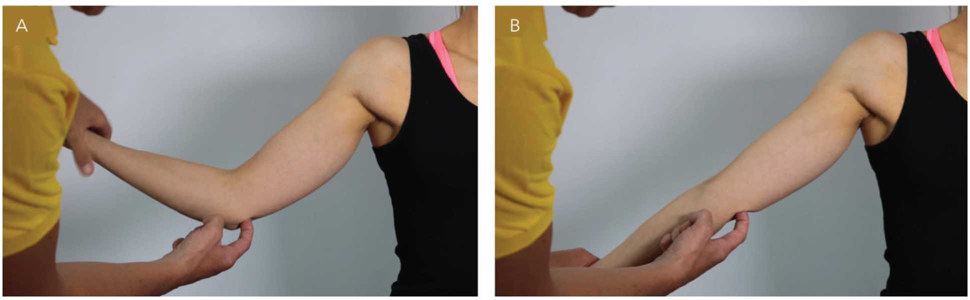

Figure 7.6 Bringing the flexed elbow (A) in terminal extension (B) typically induces pain in the posteromedial compartment in overhead athletes with posteromedial impingement. The valgus extension overload test is performed by additional application of a valgus force to the medial elbow.

early UCL symptoms, and future UCL graft failure. For example, high school and college baseball players with UCL injuries have shown impairments on balance tests compared to an uninjured cohort.[31] There is increasing interest and recognition regarding the influence of trunk and torso biomechanics, as well as leg action and stride length, on the occurrence of medial elbow injuries.[32] However, as of now (2024), we still need help to fully grasp the complexities of the human body, especially during high-intensity movements, and are limited in our abilities to effectively identify modifiable risk factors in the kinetic chain of overhead athletes with UCL injury. This topic is discussed in more detail under "prevention" below.

Conventional imaging

In throwing athletes who experience pain on the inner side of their elbow, a comprehensive assessment, including the history and physical examination of the thrower's elbow, often identifies the underlying issue. When the diagnosis is unclear or more information is required to determine the severity of the injury for adequate management, additional imaging may be necessary.[33]

Radiography

Anterior-posterior and lateral plain elbow radiographs are routinely performed before advanced imaging to assess for malalignment, fractures, arthrosis, osteochondral defects, osteocartilaginous bodies, joint effusion, and soft tissue calcifications.[34] Radiographic screening of the dominant elbow of a cohort of 56 asymptomatic Major League baseball pitchers has shown that degenerative changes, such as osteophytes, cystic changes, joint-space narrowing, and loose bodies develop over time, but correlate poorly to time spent on the disabled list or risk of future injury.[35] The utility of stress radiography of the elbow is discussed below (see *Functional imaging*, page 132).

Magnetic Resonance Imaging

MR imaging of the elbow can be used to assess UCL injury and related pathology to the posterior elbow (valgus extension overload), flexor pronator muscle mass, ulnar nerve, and radiocapitellar articulation (osteochondral defects). For this discussion, this section focuses on the MR findings specific to the UCL. Due to higher spatial resolution, MR imaging should have a minimal field strength of 1.5 to 3.0 Tesla. Some authors prefer MR arthrography with intra-articular gadolinium-based contrast to facilitate recognition of partial tears of closely apposed ligaments. In contrast, others argue that high-resolution non-contrast MR imaging is sufficient for diagnosing clinically relevant pathology.[34,36] In addition, it should be noted that MR arthrography is invasive, such that patient reluctance has also limited its routine use in elite-level pitchers, who are often highly reluctant to have contrast injected into their throwing elbow.[13] When considering MR arthrography, a posterior transtriceps approach to access the elbow joint for contrast injection may be superior to the classic lateral radiocapitellar approach (lateral soft spot), with less extra-articular contrast extravasation leading to diagnostic dilemmas.[37,38] Arguably, a posterior transtriceps approach may also decrease the risk of iatrogenic damage of cartilage.

The intact UCL is thin, vertically oriented, and has a low-signal intensity reflecting the highly organized type I collagen.[33] The proximal attachment of the anterior bundle at the medial epicondyle is quite broad, and interdigitation of fat can be seen at the posterior band, resulting in a striated appearance in some patients.[39,40] The distal attachment of the anterior bundle at the sublime tubercle is narrower and continuous with the ulnar periosteum.[41] The deep muscle fibers of the m. flexor digitorum superficialis directly oppose the outer surface of the UCL.[13]

Areas of altered signal intensity, morphology, or indistinctness of the anterior bundle indicate UCL injury.[42] Discontinuity of some or all UCL fibers may be seen, with or without retraction. An (arbitrary) distinction is made between high-grade partial and low-grade partial thickness tears based on the involvement of more or less than 50% of the ligament, respectively.[43] A "T-sign" describes the appearance of fluid extending distally between the ulna and the UCL due to the stripping of the ligament's deep fibers of the sublime tubercle.[21] This radiographic sign was initially described with computed tomography and MR arthrography but can also be observed on MR imaging without intra-articular contrast, especially with high-resolution, fluid-sensitive intermediate echo time FSE sequences.[13,41] An acute distracting force on the UCL may result in a stretched, mildly attenuated, and diffusely hyperintense ligament, reflecting the presence of interstitial micro-tears without well-defined partial thickness tears.[13] In acute UCL injuries, MR imaging may show adjacent soft-tissue edema and flexor pronator muscle mass injury.

Chronic repetitive stress may lead to ligament remodeling and thickening, resulting in altered signal intensity on MR imaging. These changes may already be seen in asymptomatic overhead athletes and are common in baseball pitchers. The anterior bundle may appear lax, redundant, or indistinct and associated hyperintensity is attributed to chronic micro-tears, leading to hemorrhage and edema.[44] An apparent sign of chronic overload and repetitive (micro) injury to the UCL is the presence of intraligamentous calcifications and heterotopic ossification. MR imaging may also show osseous stress reactions, manifesting as focal bone marrow edema patterns or osseous remodeling at the UCL's ulnar or humeral attachment site.

In the skeletally immature athlete, acute and chronic stress to the UCL is transmitted to the 'weaker' medial epicondylar apophysis. Chronic stress may result in Salter-Harris type I fractures with variable degrees of separation, often without significant observable changes to the UCL itself (also called "Little league elbow").[45] Traction apophysitis may be seen, with widening of the growth plate or fragmentation of the epicondylar apophysis.[13] After growth plate closure (i.e., physeal fusion), a bulbous contour of the medial epicondyle may indicate prior apophyseal injury.

Functional imaging

Conventional imaging techniques offer a static view of the elbow, falling short of providing a dynamic assessment of UCL competence. In response to this limitation, innovative imaging strategies have merged to enable functional evaluations of the UCL, including stress radiography and dynamic stress ultrasonography.[13]

Stress radiography

As plain radiography cannot provide direct evidence of soft tissue injury, stress radiography has been advocated to evaluate functional UCL laxity.[27,46] In 1998, Lee and colleagues evaluated the amount of radiographic medial joint space gapping with standardized valgus stress in a nonathletic cohort of 40 men and women without a history of elbow trauma or instability. They observed no significant difference in joint gapping between the non-dominant and dominant arms.[47] A similar study was performed among professional baseball pitchers that same year, providing the first evidence of increased medial elbow laxity in the dominant elbow of asymptomatic overhead athletes. In this cohort, the authors observed more medial elbow gapping of the throwing elbow than the non-throwing elbow (1.2 mm vs. 0.88 mm, respectively).[27] In 2000, Eygendaal and colleagues described the findings of valgus stress radiography in a European cohort of sixteen overhead athletes with medial elbow instability, observing increased medial joint gapping of 3 to 6 mm of the injured elbow compared to the uninjured elbow in the majority of patients with UCL avulsions or mid-substance ruptures.[48]

Some authors argue that stress radiography may benefit athletes with high clinical suspicion for medial elbow instability and unclear MR imaging findings.[34] In the study presented in chapter 4 of this thesis, we explored the findings of stress radiographs performed in the workup of a clinical cohort of 74 patients with throwing-related medial elbow pain. Medial joint space measurements were performed on the available stress radiographs and correlated to UCL injury severity on MR imaging. While unilateral joint gapping of the injured elbow (i.e., the amount of widening of the joint space when applying valgus stress) was related to UCL injury severity on MR imaging, bilateral differences in joint opening under valgus stress did not reach significance among UCL injury severity groups. In addition, approximately one in five patients (22%) showed more gapping of the uninjured elbow than the injured elbow. This finding was consistent with previous observations by Bruce and colleagues in 2014 but striking given the expected UCL laxity of the thrower's elbows. We did not find associations between this "negative excess" opening of the injured elbow and patient characteristics that may subscribe to a theory of guarding of the elbow (due to pain or anxiety) or mechanical obstruction (i.e., due to posteromedial osteophytes or loose bodies). This phenomenon remains poorly understood.

The lack of association between UCL injury severity and level of bilateral joint gapping implies that the added value of stress radiography in the workup of throwing athletes may be limited. Findings of stress radiography significantly depend on standardization of radiographic procedures and measurement methods, and the ability to do so may be challenging in day-to-day clinical care. Furthermore, stress radiographs are still limited because the UCL is not visualized directly and the medial joint opening is measured indirectly – by measuring the delta of the bone-to-bone distance of the ulna and medial epicondyle.

Stress ultrasonography

Ultrasonography is a real-time imaging modality that allows for the dynamic evaluation of the UCL and addresses several drawbacks of conventional (static) imaging modalities and stress radiography.[49,50] The use of ultrasonography or ultrasound has notably increased in a various clinical settings over the past decades (e.g., at emergency departments, outpatient clinics, and athletic training rooms). It is currently performed by a variety of healthcare providers, including ultrasound technologists, physicians, physical therapists, and athletic trainers.[13] Musculoskeletal ultrasonography utilizes reflected pulses of high-frequency sound waves to visualize and assess tendons, ligaments, muscles, nerves, vessels, joints, cartilage, bone surfaces, soft tissue masses, and fluid-contained structures. The medial elbow is suitable for ultrasonography due to its superficial anatomy and limited subcutaneous adipose tissue.

Ultrasound transducers for musculoskeletal imaging have axial resolutions ranging from 0.15 mm (at 10 MHz) to 0.04 mm (at 20 MHz), enabling the depiction of fine anatomic changes that may be difficult to depict with other imaging modalities.[13] However, the quality of ultrasonography is highly operator-dependent due to its dynamic nature. Proper training and substantial experience in musculoskeletal ultrasonography are required to limit and adequately interpret

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Stress radiography of the elbow - providing an indirect assessment of the functional competence of the UCL - may be of limited use in the clinical workup of throwing athletes with medial elbow pain. Results of clinical stress radiography poorly distinguish physiological UCL laxity and pathological UCL insufficiency.

various common imaging artifacts related to the ultrasonography technique, such as anisotropy, acoustic shadowing or enhancement, reverberation, and edge shadowing. A comprehensive bilateral medial elbow ultrasound can be performed in approximately 10 minutes.[51] The primary UCL abnormalities that can be observed with ultrasonography are thickening of the anterior bundle, in-substance hyper-echogenicity with or without acoustic shadowing indicating calcifications, and hypo-echoic foci or tissue fiber disruption with anechoic fluid within a tear.

The earliest description of the application of ultrasonography to UCL injury and the modality's unique ability to directly measure the amount of medial joint space widening occurring with valgus stress was published in case reports in 2002.[52,53] In corroboration with previous findings on stress radiography, ultrasonography has been utilized to demonstrate that the ulnohumeral joint space of the dominant elbow is significantly wider under valgus stress conditions compared to the non-dominant elbow in asymptomatic baseball players.[27,51,54] In addition, significant asymptomatic thickening, hypo-echoic foci, and calcifications of the anterior bundle of the UCL of the dominant elbow have been observed in non-injured Major League baseball pitchers.[51] It has been shown that the mean UCL thickness measured with ultrasonography significantly increases with years of professional experience among asymptomatic young professional pitchers (17-21 years).[55] In this cohort, other parameters, such as joint gapping, presence of calcifications, or heterogeneity, did not differ as years of professional experience increased. Similar findings have been observed in younger age groups (12-18 years), with correlations between higher pitching workloads and UCL thickening on ultrasonography.[56] A 2021 study has even shown an increase in UCL thickness after one season of competitive collegiate baseball pitching, comparing pre- and postseason measurements with dynamic ultrasonography.[57] These studies suggest that UCL thickening may be the earliest adaptive or pathologic change to occur in response to the significant stresses of pitching.[13]

In a large study by Ciccotti and colleagues (2014), annual pre-season standardized stress ultrasonography examinations have been performed in asymptomatic US professional baseball pitchers over a 10-year study period.[58] The authors observed thickening of the UCL and the frequent occurrence of hypo-echoic foci and calcifications in the dominant elbow of elite pitchers. Interestingly, the authors also observed a gradual increase of ulnohumeral joint gapping of the dominant arm in pitchers that underwent multiple stress ultrasonography evaluations over the years. Of the 368 pitchers, only twelve sustained subsequent UCL injuries requiring surgical reconstruction during the study period. Ultrasonographic findings of this small subgroup were trending toward significance for increased ligament thickness, joint gapping, hypo-echoic foci, and calcifications. The clinical implications of the ultrasonography findings were difficult to assess given the small percentage of pitchers that sustained a significant UCL injury during the study period.

Ciccotti's study group has performed multiple other studies on the use of ultrasonography for UCL injury, including cadaveric studies to determine a threshold in ultrasonographic ulnohumeral joint opening for clinically significant UCL injury.[13,59] Based on their findings, the authors have adopted a threshold of 1.4 mm increased joint space width with applied stress in the dominant compared to the non-dominant arm as in vivo clinically significant UCL injury.[13] At their institution, the authors utilized a combined diagnostic approach and established a clinical algorithm based on their cumulative experience on imaging of the thrower's elbow, with the combination of MR arthrography and stress ultrasonography resulting in a reported sensitivity, specificity, and accuracy for UCL injury of 96%, 99%, and 98%, respectively (figure 7.7).[60,†] A returning feature in their proposed clinical algorithm is the identification of kinetic chain defects. Indeed, the utilization of the human body as a kinetic chain to generate force and velocity for high-intensity movements is generally accepted, but our understanding of the underlying complexity of how we make our bodies move and the identification of modifiable and non-modifiable components of our movement apparatus is still in its infancy (see *Understanding the human body as a dynamic system*, page 142-147).

† Sensitivity, specificity, and accuracy for UCL injury for MR arthrography alone were 81%, 91%, and 88%, respectively, while ultrasonography alone resulted in 96%, 81%, and 87%.

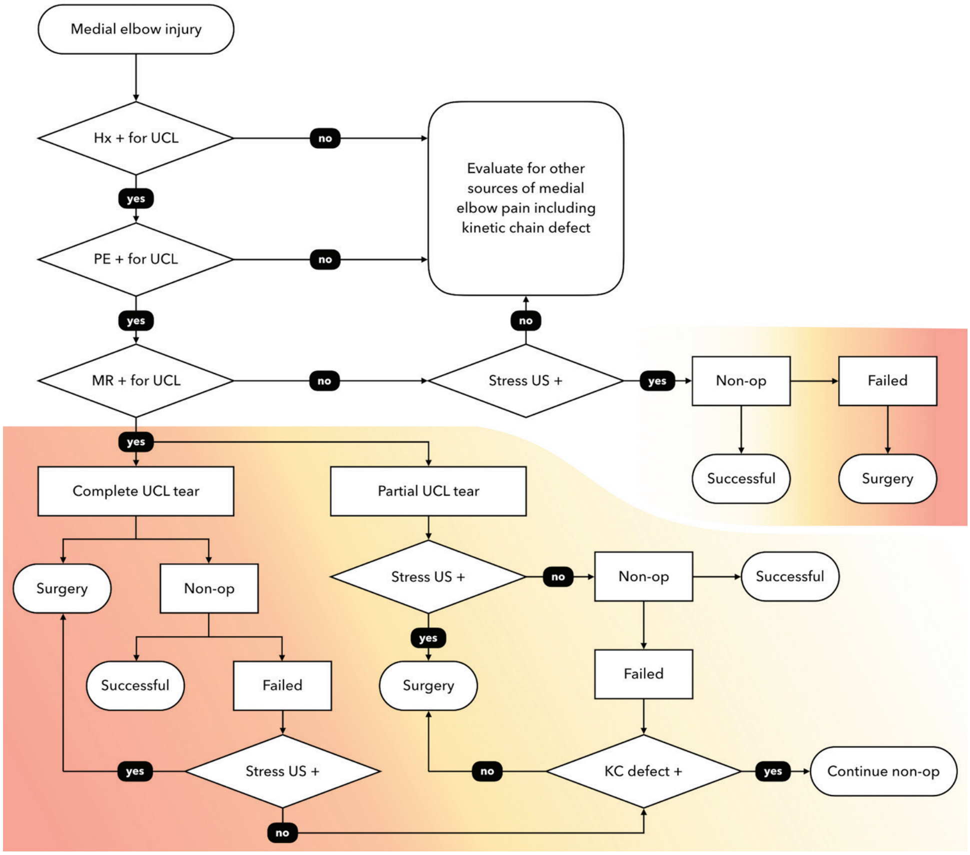

Figure 7.7 Clinical algorithm as coined by Ciccotti *et al*. (2021) for the diagnosis and management of ulnar collateral ligament (UCL) injury, including appropriate use of stress ultrasonography (US). *Hx*, history; *PE*, physical examination; *MR*, magnetic resonance (with or without intra-articular contrast); *Non-op*, non-operative treament; *KC*, kinetic chain.

Treatment

Surgical reconstruction is the cornerstone of treating significant UCL injuries in throwing athletes. As highlighted in Chapter 2 of this thesis, Dr. Frank W Jobe first performed this surgical procedure in the mid-70s, when tearing of the UCL meant the end of a professional career in baseball pitching. Over the years, various modifications of "Tommy John surgery" have been developed, and the outcomes of these techniques are pretty consistent. In the hands of experienced surgeons, the implications of suffering a UCL tear and undergoing reconstructive surgery for throwing athletes are to some extent similar to ACL tears of the knee in pivoting sports: return to the previous level of sport is expected but requires a lengthy and strenuous rehabilitation period of approximately twelve months. Furthermore, in accordance with ACL ruptures, tearing the UCL at a young age (before arriving at the professional level) dramatically decreases the chances of becoming a professional baseball pitcher, as valuable time in a *survival of the fittest* environment is lost during rehabilitation.

Although frequently depicted as relatively 'simple' collagen cords connecting two bony attachment sites, ligaments are, in reality, complex three-dimensional structures – often closely intertwined with articular capsules and consisting of several functional bands or layers of collagen fibers that provide various degrees of stability in different joint positions. For the UCL, the anterior band of the anterior bundle provides most stability in positions of relative elbow extension, while the posterior portion of the anterior bundle is more taut in flexion angles of the elbow.[61] In the study presented in Chapter 5 of this thesis, describing the pathoanatomy observed during UCL reconstruction in a large single surgeon cohort, we observed that partial UCL tears at the distal attachment site of the UCL predominantly affected the anterior band of the anterior bundle. In contrast, partial tears at the proximal attachment site mainly affected the posterior band of the anterior bundle. In the cadaveric study mentioned above, Ciccotti and colleagues (2014) determined the relative contributions of various parts of the UCL to valgus stability. They observed that the release of either the anterior or posterior band of the anterior bundle increased joint space on ultrasonography by a mean of 2.0 mm and 1.4 mm, respectively.[59] Interestingly, the location of the simulated partial tear resulted in different degrees of increased joint gapping with valgus stress – some partial tears more closely approximated the stability of an intact anterior bundle, while others behaved similarly to complete UCL tears.

There are various reasons to opt for non-operative management of UCL injury. Non-operative management can be a valuable option for non-throwing athletes and lower-demand patient populations, high-demand overhead athletes with partial UCL tears or sprains, young patients, and suboptimal seasonal or career timing (for example, in case of an older athlete that prefers to defer prolonged postoperative recovery time with surgical intervention).[62] These examples further illustrate the importance of discussing patient-specific goals and injury characteristics before deciding on a course of treatment.

There is an ongoing debate on UCL tear patterns and whether or not the decision to go for a trial of non-operative treatment depends on specific tear patterns. Some argue that there are partial tear patterns that are more likely to respond to a trial of non-operative treatment than others, which, in turn, would benefit most from early reconstruction.[13,63] A 2017 case-control study looking for MR imaging predictors of failure of non-operative management of UCL injuries‡ in thirty-two professional baseball pitchers found that 82% of failures were athletes with distal UCL tears (9/11), compared to 19% of athletes with proximal UCL tears.[64] Adjusting for age, location, and chronic attritional changes, the likelihood of failure was 12.4 times greater for athletes with distal tears. Definitive predictors for success and failure of non-operative management of UCL injuries are not yet established.

PRACTICE PEARL

Injuries to the anterior bundle of the UCL are a heterogeneous entity. There is ongoing academic discussion on whether the healing capacity of the anterior bundle varies among different locations and morphologies of partial tears.

RISK FACTORS AND PREVENTION OF UCL INJURIES

Established risk factors

In the youth and adolescent age group, pitching volume is the most significant known predictor of UCL injury.[65] The increase of early sport specialization§ – defined as the intensive training or competition in a single sport by children younger than 12 years old for more than eight months per year – has led to young players playing baseball year-round, resulting in more overuse.[66] In time, overuse may lead to arm pain and severe injury to the elbow.[67] Continuation of pitching despite arm pain is not uncommon among young baseball players and has been reported by 46% of players in a 2015 survey.[68]

Other risk factors for UCL injury in the youth and adolescent age group are pitching while fatigued, increased velocity (likely due, in part, to more frequent radar gun use to measure pitching velocity in young age groups), early

‡ Success was defined as a return to the same level of play or higher for at least one year; failure was defined as recurrent pain or weakness requiring surgical intervention after a minimum of three months' rest when attempting a return to throwing rehabilitation program (Frangiamore, *et al.* 2017).

§ The increase in early sports specialization has been attributed to the widespread belief (of athletes, parents, and coaches) that it is a requirement for excellence in sports and, therefore, to obtain a college scholarship or become an elite athlete. There is no evidence to support this belief, although there is evidence that early sports specialization increases injury risk and burnout.

maturity and pitcher height, and various factors associated with a large pitching volume, such as playing for traveling teams or more than one team, participation in showcases, pitching while also playing catcher, and months played per season).[69-73,¶] The most significant risk factors for injury requiring shoulder or elbow surgery were the number of pitches per appearance greater than 80 pitches, fastball speed >85 mph, and pitching with arm fatigue. There is no evidence for an increased UCL injury risk with specific pitch types, such as curveballs.[74]

In addition to workload-related risk factors, suboptimal throwing technique is generally regarded as a risk factor for UCL injury. The discussion on 'proper' throwing mechanics and its relationship to UCL injury is very complex. However, at the youth/adolescent level, five basic pitching parameters have been associated with lower humeral internal rotation torque (HIRT), lower elbow valgus load (EVL), and higher pitching efficiency. Lower forces across the elbow were seen in youth and adolescent pitchers when more of these parameters were performed correctly, with the hand-on-top and closed shoulder positions independently associated with lower HIRT and EVL.[75] Due to the association of GIRD and impaired balance with UCL insufficiency, the integration of a stretching and strengthening program that focuses on an improved range of motion of the shoulder, elbow and hips, strengthening of the rotator cuff, scapular stabilizers, core and lower extremities, and proprioceptive training into an athlete's sports routine is thought to decrease injury risk.[13]

Established risk factors for UCL injury at the professional level include pitching mechanics and release point,[76] arm fatigue, pitch type[**], and peak velocity.[77] Interestingly, pitching volume does not appear to be a significant risk factor for professional baseball pitchers, contrasting the findings in younger age groups.[78] Revision UCL reconstruction is more commonly performed in professional pitchers who underwent primary surgery at a younger age and those with less Major League experience, highlighting the importance of early overload prevention.[79] Therefore, UCL injury prevention in baseball starts in youth.

Current preventative measures

It is widely accepted that UCL injury in overhead athletes is caused by overuse (wear-and-tear) of the medial elbow. However, preventative measures "fall upon deaf ears," as Dr. James Andrews highlighted in the Supplemental material of Chapter 2 of this thesis. The website *Pitch Smart* (https://www.mlb.com/pitch-smart) is a collaboration between Major League Baseball, USA Baseball, and

¶ Pitchers who play more than eight months per season have a five times higher likelihood of sustaining a shoulder or elbow injury that requires surgery than those who play less than eight months per year.

** Major league pitchers throwing a higher percentage of fastballs (>48%) have a higher risk for UCL injury, which increases by 2% for every 1% increase in fastballs thrown (Keller, *et al.* 2016).

Table I. Pitch count limits and required rest recommendations.

Age	Daily max (pitches in game)	Days rest					
		0	1	2	3	4	5
7-8	**50**	1-20	21-35	36-50	-	-	-
9-10	**75**	1-20	21-35	36-50	51-65	66+	-
11-12	**85**	1-20	21-35	36-50	51-65	66+	-
13-14	**95**	1-20	21-35	36-50	51-65	66+	-
15-16	**95**	1-30	31-45	46-60	61-75	76+	-
17-18	**105**	1-30	31-45	46-60	61-80	81+	-
19-20	**120**	1-30	31-45	46-60	61-80	81-105	106+

From: https://www.mlb.com/pitch smart/pitching-guidelines; - = N/A

sports medicine experts. It offers an extensive resource for safe pitching practices, incorporating restrictions on pitch counts and innings, and safety guidelines that players and coaches can adhere to to prevent overuse injuries (table I). Pitch count limits are considered the most accurate and effective means to limit the likelihood of pitching with fatigue and thus reduce the risk of UCL injury.

Despite the critical concern of injury prevention with athletic activity, training programs are limited to the *Thrower's Ten*-exercise program variations.[62,80,81] The original Thrower's Ten included isotonic internal and external rotation in zero and 90 degrees of shoulder abduction and shoulder and scapular strengthening exercises. To enhance the transition from rehabilitation to more specific training, Wilk and colleagues (2011) introduced the *Advanced Thrower's Ten*, adding progressive challenges to postural muscles and endurance exercises to decrease muscle fatigue and increase neuromuscular control.[62] In 2012, Crotin & Ramsey introduced the *Pitchers Baseball Bat* Training Program, specifically designed for youth athletes (age six and older), including seven exercises to reduce medial elbow injuries to be performed after outings (as cooling down) and on "off-days'.[82] This program complements the Thrower's Ten with several flexor-pronator mass exercises. There are currently no studies related to the ability of these programs to reduce or prevent UCL injuries.[62]

The only study that has evaluated its effectiveness as an intervention program to prevent medial elbow injuries originates from Japan.[83-85] The efficacy of the *Yokohama-9* (YKB-9) program[††] was evaluated by the follow-up of 300

†† The YKB-9 was designed to improve physical parameters that have been previously identified as risk factors for throwing injuries (Sakata, *et al.* 2017), including nine stretching exercises that are geared to improve the range of motion of the elbow, shoulder, hip, and posture, and nine strengthening exercises focusing on the rotator cuff muscles, scapular function, and lower extremity balance.

youth baseball players divided into an intervention and control group. The intervention group completed the 20-minute YKB-9 program at least once a week during warm-up or at home. The intervention group significantly reduced the incidence rate of medial elbow injury at one-year follow-up (12.5% versus 25.4%, $P = .016$). Furthermore, the authors observed improvements in physical function in the intervention group that were predictive of a lower injury rate: increased total range of shoulder rotation (dominant side), increased hip internal rotation (non-dominant side), and decreased thoracic kyphosis angle.[83]

Why is prevention of UCL injuries so complicated?

The recent increase in elbow overuse injuries in younger baseball players has been partially attributed to a lack of awareness of the current recommendations and risk factors.[86] A 2018 survey, for example, has shown low compliance to age-appropriate pitch counts by coaches (44%), with only 13% of coaches being able even to identify risk factors.[87] Furthermore, there are widespread public misconceptions regarding risk factors for UCL injury and the assumed benefits of UCL reconstruction.[88] Medical professionals have a role to play in addressing these misperceptions and educating these athletes, parents, and coaches on risk factors and current safety guidelines.[13]

Various factors beyond a lack of awareness may explain the poor compliance with current workload guidelines. Despite their widespread occurrence, UCL injuries remain unpredictable. There is no straight line between the number of pitches or innings and injury risk, and there are (historic) examples of professional baseball pitchers with large workloads who never tore their UCL. The lack of definitive proof on the effectiveness of pitch count limits and the potential financial implications of "making it into the Big League" create incentives for individual aspiring athletes to take their chances at a college grant, scholarship, and professional career by pitching as much as they can (attending showcases throughout the country) and as fast as they can (facing a stand full of scouts watching their radar guns). In baseball pitching, high velocity imparts an advantage by increasing the likelihood of strikeouts. Consequently, it is unlikely that pitchers will throw with lower velocity to avoid injury.[13]

At most, only about 25 percent of population health is attributable to healthcare. A full fifty percent is determined by social and economic environments. In my view there is plenty of reason to think that even this fifty percent is a serious underestimate.

GABOR MATÉ, from: *The Myth of Normal (2022)*

In addition, cultural factors may also come into play. For example, the workload of pitchers in Japan is driven by a sports culture that values stamina as well as velocity, covering it with the mythical layer of *Bushidō*.[90,‡‡] Assuming that the factors above will frustrate attempts to reduce the workload among young pitchers in the near future, the question arises if there are any effective interventions to 'protect' the UCL during throwing. For example, by optimizing dynamic stabilizers around the elbow, increasing emphasis on strength and coordination of the lower kinetic chain (legs, trunk), and altering training regimens – improving variability in training impulse and focusing on self-organization of the human body as a dynamic system.[91,92]

Understanding the human body as a dynamic system

From reductionism to complexity

Preventing injuries is a crucial aspect of sports medicine with significant implications for athletes' well-being and performance. Despite considerable efforts, accurately predicting injuries remains a formidable challenge. Various common sports injuries, such as hamstring strains, patellar tendinopathy, and UCL injuries, have proven elusive in consistently identifying predictive factors through correlation and regression analysis.[93,94]

While biomechanics have traditionally employed kinematic and kinetic analysis to explore the origins of throwing injuries, these methods have not provided rehabilitative measures for UCL injuries.[95] Such analyses often adopt a reductionist perspective, breaking down athletes' injuries into isolated components and explaining them through linear, one-directional causality. However, this model may oversimplify the complexities of the human body.

The existing literature on UCL injury prevention faces limitations due to persistent attempts to identify predictive factors using unidirectional and analytical approaches. These methods overlook the multifaceted and intricate conditions contributing to sports injury occurrences.[94,96] To gain a more comprehensive understanding, we may need a broader approach that considers the dynamic nature of sports injury etiology and explores the complex relationships between risk factors and injuries.[93,97]

In 2007, Meeuwisse and colleagues introduced a model recognizing sports injuries' non-linear and recursive characteristics.[98] Combined with the 'web of determinants', describing the non-linear interactions between risk factors, this resulted in the proposition of a complex systems approach by Bittencourt and colleagues (2016).[93,99] At its core, this approach focuses on identifying relationships among injury determinants that support the emergence of injuries

‡‡ Bushidō ("the way of the warrior") is a Japanese moral code concerning samurai attitudes, behavior, and lifestyle.

The body is an amazing system. An engineer will tell you the importance of understanding how one part of any system relates to the other. This concept is sometimes overlooked in traditional Western medical models.

DONNA D ALDERMAN, from: *Integrative Pain Management (2016)*

and not on the contribution of isolated factors.[96] Ultimately, pattern recognition techniques should enable the identification of risk profiles for individual athletes or groups. Recognition of the web of injury determinants for UCL injury may increase our ability to identify effective preventative strategies.[97,100]

PRACTICE PEARL

Simply looking for individual risk factors has not provided effective solutions for UCL injuries. We may need a more comprehensive approach that recognizes the complex and interconnected nature of sports injuries. This involves focusing on the relationships among different determinants to better understand how injuries occur.

Throwing technique and the kinetic chain

Accepting the human body as a complex dynamic system also has consequences when thinking about 'proper' throwing mechanics and kinetic chain defects, frequently mentioned as important factors in UCL injury prevention (and sports injury prevention in general). Although the importance of the kinetic chain for effective throwing has been widely accepted, the implications of this fact and the identification and modification of kinetic chain deficits are currently not evidence-based. As a clinician, it is tempting to adopt the reductionist view and look for easily recognizable factors for intervention. However, the workings of the human body are incredibly complex, especially in high-intensity movements, such as baseball pitching.[91] Numerous factors come into play, and minor disturbances may have unpredictable implications. Focusing on absolute values and specific joint angles (in terms of throwing technique) easily overlooks the complexities of the human body, the variability in anatomy among individuals, and the individual's capacity to adjust mechanics while maintaining athletic performance (box 7.3, figure 7.8).

In a review from 2012, Hamill and colleagues emphasized the significance of variability, specifically the variability in the interaction between body segments or joints, in overuse injuries. This review identified two types of variability: 'end-point' variability and coordinative variability.[95] Surprisingly, several studies have found increased coordinative variability when comparing the movements of experts and novices in specific tasks.[§§] The coordination and control of human movement involves multiple degrees of freedom, which can contribute to this dynamic variability. An increasing body of literature highlights the positive and adaptive aspects of variability in how systems – presumably also the human body – function.[91,95,101]

BOX 7.3
COMPARISON OF TECHNIQUE IN ELITE JAVELIN THROWERS

In his book *Anatomy of Agility: Movement Analysis in Sport*, Frans Bosch, an authority in the field of athletic performance and rehabilitation, stages two elite javelin throwers who show very different postural characteristics just before javelin release. In the debate of 'what is a good technique,' there is support for both executions.

Advocates of the 'technique' on the left of figure 7.8 claim that the trailing right knee should stay flexed and be "dragged" towards the pivoting left leg. Meanwhile, proponents of the 'technique' on the right of figure 7.8 claim that the right leg should be actively extended against the pivoting left leg.

Bosch hypothesizes that both athletes have developed techniques that optimally protect and utilize their individual bodies. Assuming that movement capabilities of the elbow and the 'optimally protected position' of the elbow joint are dependent on bony morphology, Bosch, following an anatomy-based reasoning model, assumes that the elbow position that optimally protects the elbow joint is approximately

§§ Experts at a pistol-shooting test had less 'end-point' variability - i.e., the ability to hold the barrel of the pistol steady - but more coordinative variability between shoulder, elbow, and wrist than novices. (Arutyunyan, *et al.* 1969)

90 degrees of flexion in the athlete on the left and approximately 60 degrees of flexion in the athlete on the right. Concurrently, the shoulder joint is universally stabilized in approximately 90 degrees of abduction by co-contractions around the shoulder girdle.

In order to throw the javelin in the sagittal plane (which is essential for effective throwing), the athlete on the left maintains a straight shoulder line, while the athlete on the right needs to bend his trunk to the left to achieve this. Because of the narrow force-length relationship of the abdominal muscles and the need of these muscles to produce high forces during throwing, the pelvic line needs to be more or less parallel to the shoulder line. Hence, the athlete on the left maintains a horizontal pelvic line by upholding a flexed trailing leg knee position. In contrast, the athlete on the right has to lift the ipsilateral pelvis and does so by extending the ipsilateral knee. Bosch concludes by stating:

> *Because [the athlete] has to stay within the bandwidth of healthy movement, anatomical requirements for body movement, such as small differences in the morphology of bony structures of the elbow, can only meet the requirements of optimal external biomechanics to a limited extent.*

Figure 7.8 Different postural characteristics in two elite javelin throwers at object (javelin) release. *Reused with permission from F. Bosch*.

An ecological approach to skill acquisition

There are still many people who believe in an ideal technique and prescription. Although this discussion takes place in the domain of athletic training and skill acquisition, some understanding of the developments in these fields is also important for sports medicine physicians, especially when involved in the care of athletes. The traditional 'information processing' approach and the emerging 'ecological' approach fundamentally differ in their assumptions for skill acquisition and lead to significant differences in training methods.

According to the contemporary ecological approach to skill acquisition, no "one correct technique" exists. Athletes need to learn a set of movement solutions that is optimal for their own constraints through exploration and self-organization. There is no core set of invariant features of a generalized motor program. Skill emerges through an interaction of task, environment, and organism and their constraints (Newell's constraints model). However, due to the nature of coordination, some invariant features will emerge for almost all athletes executing a given skill; these are called "attractors" (points of stability in the movement). More than posture, these attractors are mostly about controlling forces (by co-contraction) and emerge due to stability mechanisms in the system. Strengthening of these attractors leads to increased robustness of the athlete.[91,102]

In this sense, skill development involves establishing and maintaining a relationship with the environment. In terms of coaching, the athlete establishes a relationship with the environment and should be allowed self-organization and repetition without repetition (i.e., allowed variability to adjust to the conditions). Skill training should provide the athlete with opportunities to become a movement problem solver – being able to correct "errors" and find movement solutions that are in tune with the athlete's body. Furthermore, skill training should push the athlete away from ineffective, inefficient, and injury-prone movement solutions instead of pulling athletes towards correct movement solutions (destabilization). By definition, training according to these principles is much more individual than tradition training methods that aim for a 'perfect' technique.

The goal of variability in practice, according to the ecological approach, is enhancing adaptability. Training should encourage the athlete to explore the perceptual-motor landscape (often outside of any condition the athlete will face in competition) and learn to pick up information and self-assemble coordination solutions. The goal here is repetition without repetition by adding variability – teach the athlete how to repeat a good outcome without repeating the movement. The current theory is that this variability may be introduced early, encouraging exploration and limiting the development of inefficient attractors or solutions with poor transfer. In order to achieve sufficient variability, these training methods involve conditions that are not necessarily representative of competition; for example, different weighted or sized baseballs and variations in surface and body postures).

Training methods following this 'new' approach are only now taking hold in the US, with Dutch pioneers involved in its implementation in Major League baseball organizations.[103,104] It is hypothesized that skill development through implicit learning results in healthier movement behavior and, thus, fewer injuries. Long-term follow-up of implementing these training strategies will show if the fundamental changes in training practices increase pitchers' resilience to UCL injuries and decrease UCL injury rates. In addition, future studies should establish the 'safe' spectrum of training variability for specific athletic skills and injury risk. For example, the use of under and overweight baseballs in velocity enhancement programs has been shown effective but also led to significantly more elbow injuries in pitchers during training or the following season in a 2018 randomized controlled trial.[62,105,106]

UCL INJURIES IN TENNIS: THE DUTCH PERSPECTIVE

Overhead athletic activities share striking similarities in upper extremity and kinetic chain action (see *Introduction, figure 1.5*). The repetitiveness and force of overhead activity determine the subsequent risk of overuse elbow injury. Both these factors vary significantly across overhead sports and thus influence the occurrence of (non-traumatic) UCL injury.¶¶ Because baseball pitching is – as per the design of the game – both repetitive (starting pitchers perform approximately 100 pitches per game) and highly focused on velocity (most of the time, pitchers throw the baseball as fast as they can), UCL injuries are typically affecting baseball pitchers.

Overhead activities in other sports are usually less repetitive and provide more room for movement variation and sub-maximal effort.[107] For example, in American football, handball, and volleyball, athletes can move freely on the field or court (as opposed to the baseball pitcher who is restricted to the mount) and have bigger targets (comparing the strike zone in baseball and goal or opposite court in handball and volleyball, respectively). As a result, in these sports, ball placement can be as important as velocity in terms of outcome (winning), accommodating more movement variation and lower forces on the elbow.

Compared to most other overhead sports, the repetitiveness of serving in elite tennis is equal to that of baseball pitching, with professional male and

¶¶ Traumatic ulnar collateral ligament injuries are outside the scope of this thesis; these injuries mainly occur in contact and collision sports (such as judo, water polo) due to a forceful hyperextension/valgus trauma mechanism. Because the UCL has not been exposed to the repetitive strain of overhead athletic activity, these injuries are predominantly avulsion-type injuries with good substance quality of the anterior bundle tissue fibers and are more amenable to primary UCL repair (with shorter postoperative rehabilitation time compared to UCL reconstruction).

female tennis players averaging 157 and 96 serves per match, respectively. In junior male and female tennis players, these numbers range from 86 to 94 serves per match.[107] Video analysis has demonstrated a rapid extension of the elbow similar to pitching (from 116 degrees to 20 degrees of flexion in 0.21 seconds) and ball impact during tennis serving at elbow flexion angles of approximately 35 degrees.[108] However, the late cocking and early acceleration phases of the service motion produce the highest internal forces and are thought to pose the most significant risk of injury.[109] A recent video analysis (2024) of elite male tennis players suggests a possible instant varus accommodation mechanism before hitting the ball with forehand groundstrokes as well, requiring dynamic stabilization of the elbow by the flexor muscles.[110] In general, elbow injuries observed in tennis players correlate with pitching injuries and result from a similar valgus extension overload, including UCL insufficiency, flexor-pronator tendinopathy, ulnar nerve dysfunction, posterior impingement, and osteochondritis dissecans.[111,112]

Although UCL injury and insufficiency are repeatedly mentioned in the myriad of medial elbow injuries that can occur in tennis players, these overview articles predominantly refer to baseball studies, and there is a paucity of literature specifically describing UCL injury in tennis players.[113,114] The American Sports Medicine Institute totaled its UCL reconstruction and repair operations between 1998 and 2006. It found that 1213 out of 1281 procedures were performed on baseball players, with only seven UCL procedures on tennis players.[115,116] Nevertheless, in non-throwing sports cultures, UCL insufficiency may be often misdiagnosed as flexor-pronator tendinopathy, with unnecessary delays in adequate treatment.

FUTURE RESEARCH

UCL injuries remain a significant concern in sports medicine, particularly in overhead athletes such as baseball pitchers and javelin throwers. Various issues in the diagnostic and etiological domain of UCL injuries in overhead athletes have been introduced in the previous sections of this thesis discussion. This section further explores the future perspectives on overuse UCL injuries, with a primary focus on advancements in injury risk assessment and prevention strategies for overhead athletes.

Biomechanical insights

Advancements in biomechanics have allowed researchers to delve deeper into the intricate mechanics of overhead throwing and identify factors contributing to UCL injuries. Emerging technologies, such as motion capture systems and wearable sensors, enable a comprehensive analysis of throwing mechanics, providing valuable data on joint angles, forces, and torque. Although the insights from these measurements have not had a major impact on the incidence of UCL injury among baseball pitchers, future studies may use data collected through these techniques to quantify kinetic chain deficits and establish the scientific foundation for the effectiveness of new training methods focusing on athlete's robustness. Advanced technologies may also further quantify the role of medial elbow stabilizing musculature. This knowledge will be vital to the development of targeted preventative interventions.

Imaging techniques

High-resolution MR imaging and ultrasonography offer improved diagnostic capabilities for assessing the UCL structure. These modalities allow for the early detection of subtle changes in the ligament, enabling timely intervention before severe injury occurs. Currently limited by spatial resolution compared to the small size of the anterior bundle of the UCL, imaging modalities such as diffusion tensor imaging (DTI) may further quantify tissue disruption. The distinction between physiological and pathological changes of the UCL due to repetitive overhead athletic activity remains to be further elucidated. However, advancements in imaging modalities may aid in this quest.

In search for intrinsic factors increasing the risk for UCL injury, there currently needs to be more literature on the variations in the bony morphology of the elbow. As assumed in the comparison of the throwing technique in two javelin throwers by Bosch (box 7.3), bony morphology may influence the optimal positioning of the elbow during athletic movement. Variability in prominence of the medial epicondyle or sublime tubercle alters bone-ligament-bone angles, and its influence on UCL injury risk is currently unknown. Quantitative 3- or 4-dimensional computed tomography may be utilized to quantify the normal range of bony elbow morphology and differences in bony elbow morphology of the dominant versus non-dominant arm in baseball pitchers (e.g., hypertrophic sublime tubercle or generalized hypertrophy).

Biologics and regenerative therapies

The field of regenerative medicine holds promise for UCL injury prevention and treatment. Emerging biologic therapies, such as platelet-rich plasma (PRP) and stem cell injections, aim to enhance tissue healing and regeneration. Future studies may explore the efficacy of these interventions in preventing significant UCL injuries, especially in athletes at higher risk. Additionally, advancements in tissue engineering may provide novel approaches for UCL reconstruction and repair, emphasizing restoring native tissue strength and functionality.

CONCLUDING REMARKS

Ulnar collateral ligament (UCL) insufficiency in overhead-throwing athletes remains a common problem with a complex etiology, predominantly faced by clinicians in throwing-dominant sports cultures. The optimization of guidance for throwing athletes and the reduction of UCL injury risk necessitate a comprehensive, multidisciplinary approach. Integrating biomechanics, imaging, (genetics?), load management, and regenerative therapies can synergistically advance our understanding and management of UCL injuries, ultimately fostering the long-term health and performance of overhead athletes. An overarching avenue for future research is the identification of current barriers to interdisciplinary collaboration. One of the barriers may stem from the ambiguous frameworks within which doctors (sports physicians and orthopedic surgeons), physical therapists, and researchers (biomechanical engineers) operate, delineating the specific aspects or domains of the problem for which a given discipline assumes responsibility.

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Summary

PART I

A HISTORY OF ULNAR COLLATERAL LIGAMENT INJURY

This thesis covers the topic of UCL insufficiency in overhead athletes, starting with the origins of surgical reconstruction and introducing the 'epidemic' of UCL surgery performed in young baseball pitchers in the United States. Dr. Frank W. Jobe (1925 – 2014) pioneered UCL reconstruction, also known as Tommy John surgery. Urgency and limited alternatives led to the experimental surgical procedure performed on the elbow of Los Angeles Dodgers pitcher Tommy John in September 1974, establishing a career-saving treatment option for professional baseball pitchers with UCL tears. The path from Jobe's classic work, a case series of the first sixteen patients undergoing UCL reconstruction, published in 1986, to the dramatic rise of UCL reconstructions performed in young overhead athletes over the last two decades, including the evolution of reconstruction techniques, was covered in **Chapter 2** of this thesis. In the supplemental material of this study, leading orthopedic surgeons and authorities in the field, Dr. James R. Andrews and Prof. Dr. Roger van Riet, provided their educated opinions on the current 'epidemic' of UCL injuries, return to sport decision-making and the development of new treatment modalities.

PART II

CLINICAL WORKUP OF UCL INJURY IN OVERHEAD ATHLETES

Throwing athletes sustaining a UCL injury may recall a popping sensation (feeling or hearing) originating from the medial elbow at the time of injury. This anamnestic finding is well known by clinicians involved in the care for overhead throwing athletes. However, there were no studies available that inform clinicians how to utilize this salient anamnestic information and what amount of diagnostic weight to afford it. The study in **Chapter 3** assessed the diagnostic value of a popping sensation for significant UCL injury in throwing athletes who sustained an injury causing medial elbow pain. A total of 207 consecutive patients with throwing-related medial elbow pain were evaluated for UCL injury by the senior author, and medical records were retrospectively analyzed. Magnetic resonance imaging was evaluated for UCL injury severity and classified into intact, edema/low-grade partial, high-grade partial, and full-thickness tears.

The overall frequency of a pop in this cohort was 26%, and the proportion of patients who reported a pop significantly increased with UCL tear severity from 13% in patients with low-grade UCL injuries to 26% in patients with high-grade partial thickness tears, and 51% in patients with full-thickness tears. The positive likelihood ratio, negative likelihood ratio, and odds ratio of a popping sensation for significant UCL injury (arbitrarily defined as high-grade partial-thickness or full-thickness tears) were 3.2, 0.7, and 4.4, respectively. This means that when a throwing athlete reports a pop, this should moderately increase a clinician's suspicion of a significant UCL injury. Conversely, the absence of a pop should not substantially decrease suspicion of significant UCL injury.

The findings of this study allow for the clinical interpretation of a popping sensation at the time of injury described by a throwing athlete with medial elbow pain. They can be used for diagnostic purposes as well as patient counseling. Furthermore, being the first study to focus on this well-known and salient anamnestic finding explicitly, this study provides foundation for future studies of predictive and diagnostic factors for UCL injury in throwing athletes.

The anterior bundle of the UCL complex connects the ulna's sublime tubercle with the humerus's medial epicondyle, resisting valgus luxation of the elbow joint. By attenuation or tearing of the anterior bundle, UCL insufficiency presumably leads to an increase in medial elbow joint space opening that can be measured using stress radiography. The value of stress radiography in the management of throwing athletes remains unclear. The purpose of the study presented in **Chapter 4** was to analyze the relationship between medial elbow joint opening and UCL injury severity on MR imaging and its usefulness in the clinical workup of throwing athletes. Two raters independently performed medial joint space measurements on the stress radiographs of 74 consecutive patients who underwent standardized valgus stress radiography as part of their clinical workup for throwing-related medial elbow pain. UCL injury severity was classified based on available MR imaging.

We observed that joint gapping was related to UCL injury severity, and group-level comparison showed an incremental increase of joint gapping (difference in medial elbow joint space with and without valgus stress of the injured elbow) among MRI-based tear severity groups (intact, partial-thickness tears, or full-thickness tears of the anterior bundle). Comparison of the joint opening of the injured elbow and the uninjured elbow under valgus stress was not significantly associated with UCL injury severity in our sample (excess opening; the difference in medial elbow joint space of the injured and uninjured elbow under valgus stress). Interestingly, negative excess opening (less medial joint space of the injured elbow in comparison to the uninjured elbow) was observed in

22% of patients. However, no factors corroborating guarding or a mechanical explanation were significantly associated with this observation. Designed initially to compare joint space opening of the injured and uninjured elbow, the clinical usefulness of stress radiography in the workup of throwing athletes may, therefore, be limited.

PART III
UCL PATHOANATOMY AND SURGICAL RECONSTRUCTION

It is generally accepted that non-traumatic UCL injuries are the result of wear and tear of the anterior bundle of the UCL complex. Onset of UCL injury symptoms, such as medial elbow pain, impaired velocity, precision of throwing or command, and elbow instability, are thought to be the acute part of an acute-on-chronic injury etiology. Repetitive high-intensity, high-volume throwing has weakened the UCL complex and may, over time, result in an acute tearing incident of the anterior bundle. In **Chapter 5**, we performed a descriptive analysis of the anterior bundle of the UCL in a single-surgeon series of 163 patients who underwent UCL reconstruction. Descriptions of the pathoanatomy were retrospectively obtained from the surgical inspection notes in the operative reports. The primary purpose of this study was to increase our understanding of the phenotypes of anterior bundle injuries and explore associations with demographic and clinical patient characteristics.

In this study, we objectified the assumed heterogeneity of anterior bundle injuries in patients undergoing UCL reconstruction. We observed that the anterior bundle of the UCL was disrupted singularly or at multiple locations in 65% and 23% of patients, respectively. Among these patients, various configurations were observed, including tears, perforations, and tear-perforation combinations of the anterior bundle, and attenuation and thinning at the area of disruption were frequently observed, subscribing to the acute-on-chronic etiology of throwing-related UCL injuries. Additional analysis showed a significant difference in anterior versus posterior band involvement among partial tears at the distal versus proximal attachment site of the anterior bundle; partial full-thickness tears at the distal attachment site mainly affected the anterior band of the anterior bundle, whereas tears located proximally predominantly involved the posterior band of the anterior bundle.

In the remaining 12% of patients, no distinct fiber tissue disruptions were observed, but anterior bundles were functionally incompetent due to localized or generalized signs of chronic injury, such as attenuation (this subgroup of patients was coined as having “non-tear insufficiency” of the anterior bundle).

Calcifications and loose bodies were observed in 6.1% of patients, including one patient that showed a striking phenotype of a complete tear at de midsubstance between two ossified regions of the anterior bundle with only a tiny portion of the proximal aspect of the ligament that was not ossified.

The only demographic/clinical characteristic that showed a significant difference among the observed subgroups of anterior bundle injuries was an anamnestic popping sensation at the time of injury, which was more frequently experienced by patients with anterior bundle injuries characterized by a single tear compared with patients with non-tear insufficiency.

UCL reconstruction is generally performed using a docking or modified Jobe technique with ipsilateral or contralateral palmaris longus autograft. Various alternative autografts, e.g., gracilis, semitendinosus, toe extensor, plantaris, and Achilles tendon, can be used in patients with absent palmaris longus (approximately 17% of the world population). In addition, allografts may be successfully used for UCL reconstruction. We provided an overview of the various applications and indications for the use of allografts in reconstructive surgery of the elbow and forearm in **Chapter 6**, which was written for the *ESSKA European Allograft Initiative*. The Allograft Initiative project aims to promote the availability, awareness, and cost-effectiveness of allograft tissue in reconstructive surgery in Europe.

GENERAL DISCUSSION

UCL injuries are of paramount concern in baseball cultures, such as the United States and Japan. Despite extensive research, the incidence of UCL surgeries has persistently increased over the past decades, particularly among younger demographics. This thesis delves into UCL injuries among overhead athletes, emphasizing those stemming from repetitive stress rather than acute traumatic events. Existing literature primarily emanates from the United States. In Europe, where baseball holds a more peripheral status, UCL injuries are less prevalent and underexplored among healthcare professionals in the athletic context. Consequently, this thesis aims to extrapolate insights from baseball science to inform and enhance knowledge and management strategies applicable to non-baseball overhead athletic disciplines.

The assessment of overhead athletes presenting with medial elbow pain involves a detailed history-taking process, considering symptom onset and duration. Understanding the phase of the throwing motion associated with pain aids in distinguishing various elbow pathologies, with the late cocking and acceleration phases indicating UCL injury. Secondary symptoms like cold intolerance and grip strength reduction may suggest ulnar neuropathology, necessitating differentiation between tendinopathy and ligament insufficiency for optimal management. Treatment decisions are tailored to individual circumstances, considering prior injuries, competition level, and timing within the athletic season.

A comprehensive physical examination involves bilateral comparisons and functional tests to assess joint stability and kinetic chain function. Radiography and MR imaging play vital roles in evaluating UCL injury and related pathologies, revealing morphological changes and tissue abnormalities. Stress radiography and dynamic stress ultrasonography offer innovative approaches to assess UCL function dynamically. While stress radiography measures joint laxity indirectly, ultrasonography provides real-time evaluation and direct measurement of medial joint space widening under stress. Integration of kinetic chain evaluations into diagnostic algorithms highlights the evolving understanding of injury assessment and prevention in overhead athletes.

Surgical reconstruction (Tommy John surgery) remains the primary treatment for significant UCL injury in throwing athletes, offering consistent outcomes akin to anterior cruciate ligament tears of the knee in pivoting sports. However, non-operative management may be suitable for select populations. Research suggests distal UCL tears may be less responsive to non-operative management, emphasizing the need for further investigation into treatment outcome predictors.

Pitching volume emerges as a significant predictor of UCL injuries among youth and adolescents, driven by early sport specialization and year-round baseball play, which increases the risk of overuse injuries. Despite the prevalence of arm pain, many young players continue pitching, presumably leading to more severe elbow injuries. Other risk factors include pitching while fatigued, increased velocity, and various factors associated with high pitching volume. Notably, suboptimal throwing technique also heightens UCL injury risk, with certain pitching parameters linked to higher forces across the elbow. Integrating stretching, strengthening, and proprioceptive training into an athlete's training routine is believed to decrease injury risk, emphasizing prevention starting in youth.

Efforts to prevent UCL injuries include implementing pitch count limits and training programs like the *Thrower's Ten* and the *Pitchers Baseball Bat Training Program*. However, the effectiveness of these programs remains uncertain. The *Yokohama-9 program* from Japan has shown promise in reducing medial elbow injury rates. Challenges in prevention persist due to a lack of awareness of recommendations and risk factors among coaches and the unpredictable nature of UCL injuries. Cultural factors and the pursuit of professional careers also contribute to poor compliance with workload guidelines, highlighting the need for effective interventions to protect the UCL during throwing.

Traditional approaches to injury prevention, focusing on linear causality and isolated factors, overlook the dynamic and multifaceted nature of sports injuries. A complex systems approach, considering the non-linear interactions between risk factors, may enhance our ability to identify effective preventative strategies. Skill acquisition in athletes should embrace variability and self-organization, allowing exploration and adaptation to individual constraints. Training methods following this approach aim to enhance adaptability, potentially reducing injury rates in athletes. However, long-term studies are needed to assess the effectiveness of these strategies and establish safe training variability for specific athletic skills.

Overhead athletic activities, characterized by repetitive and forceful upper extremity actions, pose a risk for overuse elbow injuries, particularly UCL injuries. The nature of these activities varies significantly across sports, influencing the likelihood of UCL injury occurrence. Baseball pitching stands out due to its inherent repetition and focus on high velocity, making pitchers particularly vulnerable to UCL injuries. In contrast, other overhead sports like American football, handball, and volleyball afford more movement variation and lower forces on the elbow, reducing the risk of UCL injury. Elite tennis, particularly serving, exhibits repetitive motions akin to baseball pitching, with comparable rates of serves per match. While UCL injuries in tennis correlate with those in baseball, literature on tennis-specific UCL injury is scarce, with most studies referencing baseball data. Nevertheless, UCL insufficiency in non-baseball sports may be misdiagnosed, leading to unnecessary delays in treatment.

Advancements in biomechanics and imaging offer promising avenues for understanding and preventing UCL injuries in overhead athletes. Biomechanical insights, aided by motion capture and wearable sensors, may inform new training methods focusing on athlete robustness. Imaging modalities like high-resolution MR imaging and ultrasonography allow early detection of UCL changes, while biologics and regenerative therapies hold potential for injury prevention and treatment. Further research is needed to explore intrinsic factors such as bony morphology variability and the efficacy of emerging therapies in preventing UCL injuries.

Nederlandse samenvatting

DEEL I

EEN GESCHIEDENIS VAN LETSEL VAN HET ULNAIRE COLLATERALE LIGAMENT

Dit proefschrift behandelt insufficiëntie van het ulnaire collaterale ligament bij bovenhandse sporters, beginnend met de ontwikkeling van de chirurgische techniek om het ligament te reconstrueren en de introductie van de actuele 'epidemie' van elleboogoperaties onder jonge honkballers in de Verenigde Staten. Dr. Frank W. Jobe (1925 - 2014) was de pionier van UCL reconstructie, ook wel bekend als Tommy John surgery. Bittere noodzaak en een gebrek aan alternatieve behandelopties leiden in september 1974 tot de experimentele chirurgische ingreep uitgevoerd aan de elleboog van LA Dodgers pitcher Tommy John. De procedure bleek carriere-reddend voor professionele werpers met letsel van de UCL. Het pad van het klassieke werk van Dr. Jobe (een case-serie uit 1986 van de eerste zestien patienten die UCL reconstructie ondergingen) tot de dramatische toename van UCL reconstructies bij jonge bovenhandse sporters in de afgelopen decennia wordt behandeld in **Hoofdstuk 2** van dit proefschrift. In het supplement van dit hoofdstuk geven vooraanstaande orthopedisch chirurgen en autoriteiten op het gebied van sportgerelateerd elleboogletsel, dr. James R. Andrews en prof. dr. Roger van Riet, hun mening over de huidige epidemie van UCL blessures, de besluitvorming rondom return-to-play na UCL reconstructie en de ontwikkeling van nieuwe behandelmodaliteiten voor UCL letsels.

DEEL II

KLINISCHE EVALUATIE VAN UCL-LETSEL BIJ BOVENHANDSE SPORTERS

Honkbal pitchers die een UCL blessure oplopen kunnen - ten tijde van het letsel - een knappend gevoel ("pop") afkomstig van de binnenzijde van de elleboog ervaren. Deze bevinding in de anamnese is bekend bij medici en paramedici die betrokken zijn bij de zorg voor werpende sporters. Echter waren er geen studies beschikbaar die clinici informeren over hoe dit anamnestische gegeven te interpreteren en welk diagnostisch gewicht eraan toe te kennen. De studie in **Hoofdstuk 3** van dit proefschrift beoordeeld de diagnostische waarde van een acuut knappend gevoel voor significant UCL letsel bij werpende sporters met mediale elleboogpijn. Hiervoor werden de klinische beoordelingen van 207 patiënten met werpgerelateerde mediale elleboogpijn retrospectief geanalyseerd.

Op basis van MRI beeldvorming werd de ernst van UCLmletsel geclassificeerd in vier categoriën: intact, oedemateus/laagradig partiëel letsel, hooggradig partiëel letsel en volledige dikte rupturen.

Zesentwintig procent van de werpers in dit cohort rapporteerde een knap te hebben gevoeld of gehoord, en een knap werd significant vaker gevoeld door werpers met ernstiger UCL letsel op MRI: 13% van de patiënten met laaggradig partiëel letsel, 26% van de patiënten met hooggradig partiëel letsel en 51% van de patiënten met volledige dikte rupturen herinnerde zich een dergelijke sensatie. De positieve likelihood ratio, negatieve likelihood ratio en odds ratio van een knap-sensatie voor significant UCL letsel (hooggradig partiëel en volledige dikte rupturen) waren respectievelijk 3.2, 0.7 en 4.4. Dit betekent dat wanneer een werpende sporter met mediale elleboogpijn een knap meldt ten tijde van het ontstaan van zijn klachten, dit de verdenking op significant UCL letsel matig moet doen toenemen. Omgekeerd dient de afwezigheid van een knap de verdenking op significant UCL letsel niet substantieel te verminderen.

De bevindingen van deze studie maken de klinische interpretatie mogelijk van een knap-gevoel op het moment van letsel zoals tijdens een consult kan worden beschreven door een werper met mediale elleboogpijn. Deze bevindingen kunnen worden gebruikt voor diagnostische doeleinden en patiëntvoorlichting. Bovendien biedt deze studie een basis voor toekomstige studies ten aanzien van voorspellende en diagnostische factoren voor UCL letsel bij werpende sporters.

De anterieure bundel van het UCL complex verbindt de ellepijp (ulna) met het mediale epicondyl van het opperarmbeen (humerus) en geeft weerstand tegen valgisatie van het ellebooggewricht. Insufficiëntie en/of rupturering van de anterieure bundel leidt tot meer speling op het mediale ellebooggewricht en toename van 'gapping' onder valgus stress. De waarde van stress radiografie - een niet-invasieve methode om de mediale gewrichtsruimte te meten - bij de klinische beoordeling van werpende sporters is onduidelijk. Het doel van de studie gepresenteerd in **Hoofdstuk 4** van dit proefschrift was om de relatie tussen de opening van het mediale ellebooggewricht onder valgus-stress en de ernst van UCL letsel op MRI te bepalen. Hiervoor werden de data van vierenzeventig patiënten met werpgerelateerde mediale elleboogpijn retrospectief geanalyseerd: stress radiografie, zoals in de klinische workup van deze patiënten opgenomen, werd door twee afzonderlijke beoordelaars gekwantificeerd ten aanzien van de mediale gewrichtsopening onder valgusstress. De ernst van het letsel werd geclassificeerd op basis van beschikbare MRI beeldvorming (intact, partiëel, volledige dikte rupturen).

Mediale gewrichtsopening van de elleboog was gerelateerd aan de ernst van UCL letsel en vergelijking op groepsniveau toonde een stapsgewijze toename van gewrichtsopening bij oplopende ernst van UCL letsel op MRI. Het verschil in mediale gewrichtsopening tussen de geblesseerde en niet-geblesseerde elleboog onder valgusstress was niet significant geassocieerd met de ernst van UCL letsel in dit cohort. Opvallend was dat een negatieve 'excess opening' (minder mediale gewrichtsopening van de geblesseerde elleboog dan de niet-geblesseerde elleboog) werd geobserveerd in 22% van de patiënten. Er werden geen factoren gevonden die de hypothetische verklaringen van afweerspanning (guarding) of een mechanische beperking van de elleboog ondersteunen.

De klinische bruikbaarheid van stress radiografie, die oorsponkelijk bedoelt is om de mediale gewrichtsopening van de geblesseerde en niet-geblesseerde elleboog te vergelijken, lijkt om bovenstaande redenen beperkt.

DEEL III

PATHOANATOMIE VAN UCL LETSEL EN CHIRURGISCHE RECONSTRUCTIE

Het is algemeen aanvaard dat werpgerelateerd UCL letsel het gevolg is van slijtage van de anterieure bundel van het UCL complex door repetatieve hoge belasting van het ligament, zoals bijvoorbeeld bij honkbal pitchen het geval is. De eerste symptomen (mediale elleboogpijn, verminderde werpsnelheid, afname van precisie of het gevoel van instabiliteit) worden beschouwd als het acute deel van een 'acute-on-chronic' etiologie. Herhaaldelijk hoog-intensief werpen heeft het UCL complex verzwakt, wat na verloop van tijd kan leiden tot een acute ruptuur van de anterieure bundel. **Hoofdstuk 5** van dit proefschift bevat de descriptieve analyse van een single-surgeon cohort van 163 patiënten die een UCL reconstructie ondergingen. Beschrijvingen van de intra-operatieve observaties van het letsel van de anterieure bundel werden retrospectief verkregen uit gedetailleerde operatieverslagen. Het doel van deze studie was om het begrip van verschillende fenotypen van UCL letsel te vergroten en associaties met demografische en klinische patiëntkenmerken te exploreren.

In deze studie werd de heterogeniteit van UCL letsel geobjectiveerd. De anterieure bundel van het UCL was enkelvoudig of meerdere plekken beschadigd bij respectievelijk 65% en 23% van de patiënten. Onder deze patiënten werden verschillende letsel-configuraties van de anterieure bundel waargenomen, waaronder scheuren, perforaties en scheur/perforatie-combinaties. Een uitgebreidere verzwakking van het ligament (uitrekking, verdunning) werd frequent waargenomen ter plaatse van het primaire letsel, passend bij de veronderstelde acute-on-chronic etiologie van werpgerelateerd UCL letsel. Aanvullende analyse toonde een significant verschil in betrokkenheid van het anterieure en posterieure deel van de anterieure bundel bij distaal en proximaal gelokaliseerde partiële UCL letsels. Partiële distale rupturen werden voornamelijk gezien in het anterieure gedeelde van de anterieure bundel, terwijl partiële proximale rupturen met name het posterieure gedeelte van de anterieure bundel aantastten.

Bij de resterende 12% van de patiënten werd geen duidelijke onderbreking van het ligament waargenomen, maar bleek de anterieure bundel functioneel incompetent als gevolg van gelokaliseerde of gegeneraliseerde verzwakking. Calcificaties van de anterieure bundel werden waargenomen in 6.1% van de patiënten, inclusief één patiënt die een opvallend fenotype vertoonde van een volledige scheur tussen twee verkalkte gebieden van de anterieure bundel, waarbij slechts een klein deel van het proximale aspect van het ligament niet verkalkt was.

Het enige klinische gegeven dat significant onderscheidend was voor letsel-fenotypen was een knap-sensatie bij aanvang mediale elleboogpijn, wat significant vaker werd gerapporteerd door patiënten met UCL letsel dat gekarakteriseerd werd door enkelvoudig letsel (één ruptuurlokatie) vergeleken met patiënten met gelokaliseerde of gegeneraliseerde verzwakking van het ligament zonder ruptuur of perforatie van het bandweefsel.

UCL reconstructie wordt over veelal uitgevoerd met een docking of gemodificeerde Jobe techniek met een ipsilaterale of contralaterale palmaris longus autograft. Verschillende alternatieve autografts - zoals gracilis, semitendinosus, extensor hallucis, plantaris en achillespees - kunnen worden gebruik bij patiënten zonder palmaris longus (circa 17% van de wereldbevolking). Bovendien kunnen allografts (niet-lichaamseigen weefsels) met succes worden gebruikt voor UCL reconstructie. **Hoofdstuk 6** van dit proefschrift geeft een overzicht van de verschillende toepassingen en indicaties voor het gebruik van allografts in reconstructieve chirurgie van de elleboog en onderarm en werd geschreven voor het *ESSKA European Allograft Initiative* dat tot doel heeft de beschikbaarheid, bekendheid en kosteneffectiviteit van allograftweefsel bij reconstructieve chirurgie in Europa te bevorderen.

ALGEMENE DISCUSSIE

UCL blessures zijn een medisch probleem in honkbalculturen, zoals die van de Verenigde Staten en Japan. Ondanks uitgebreid onderzoek is het aantal UCL operaties de afgelopen decennia gestaag toegenomen, vooral onder jonge werpers. Dit proefschrift richt zich op UCL letsel bij bovenhandse sporters ten gevolge van repetitieve (over)belasting van de elleboog (in tegenstelling tot letsel ten gevolge van een acuut trauma). Huidige literatuur over UCL letsel komt voornamelijk uit de Verenigde Staten. In Europa is UCL letsel minder gebruikelijk en minder bekend onder zorgprofessionals in de sport. Het doel van dit proefschrift is om inzichten uit de honkbalwetenschap te aggregeren en extrapoleren om kennis en behandeling voor bovenhandse sporters met UCL letsel te optimaliseren.

De beoordeling van bovenhandse sporters die zich presenteren met mediale elleboogpijn omvat een gedetailleerde anamnese, onder andere gericht op het ontstaan en de duur van symptomen. Het begrijpen van de fase van de werpbeweging die gepaard gaat met pijn helpt bij het onderscheiden van verschillende elleboogpathologieën, waarbij de 'late cocking' en 'acceleratie' fasen kunnen wijzen op UCL letsel. Bijkomende klachten zoals koude-intolerantie en vermindering van de gripkracht kunnen wijzen op ulnaire neuropathologie, wat differentiatie tussen tendinopathie en ligamentinsufficiëntie vereist voor optimale behandeling. Mogelijke behandelstrategieën zijn afhankelijk van individuele omstandigheden, waarbij onder andere rekening dient te worden gehouden met de aard van de sport, competitieniveau, timing binnen het sportseizoen en eerdere blessures.

Een uitgebreid lichamelijk onderzoek omvat links-rechts vergelijkingen en functionele elleboogtesten om de gewrichtsstabiliteit en kinetische ketenfunctie te beoordelen. Radiografie en MRI spelen een belangrijke rol in de diagnostiek van UCL letsel en gerelateerde elleboogpathologieën, waarbij morfologische veranderingen en omvang van letsel zichtbaar kunnen worden gemaakt. Stressradiografie en dynamische stress-echografie zijn innovatieve modaliteiten om de UCL functie dynamisch te beoordelen. Terwijl stressradiografie gewrichtslaxiteit indirect meet, biedt echografie een directe meting van de opening van het mediale elleboogewricht onder valgiserende stress. Integratie van evaluatie van de kinetische keten in diagnostische algoritmen impliceert een groeiend begrip van het belang hiervan in de etiologie van werpgerelateerd letsel en blessurepreventie bij bovenhandse atleten.

Chirurgische reconstructie (Tommy John surgery) blijft de primaire behandeling voor significant UCL letsel bij werpende sporters, met resultaten vergelijkbaar met die van voorste kruisband reconstructie van de knie bij pivoterende sporters. Een conservatieve benadering kan echter geïndiceerd zijn bij specifieke patientpopulaties. Onderzoek suggereert bijvoorbeeld dat distale UCL rupturen mogelijk minder goed reageren op conservatieve revalidatie dan midportion of proximale UCL rupturen.

Het aantal pitches blijkt een voorspeller van UCL blessures bij jongeren en adolescenten, wat vermoedelijk wordt gedreven door vroege sportspecialisatie en year-round baseball, wat het risico op overbelastingsblessures vergroot. Ondanks armklachten blijven veel jonge spelers werpen, wat hypothetisch leidt tot de ontwikkeling van ernstigere elleboogblessures. Andere risicofactoren voor UCL letsel zijn werpen ondanks vermoeidheid, hogere werpsnelheden en verschillende factoren die verband houden met een hoge pitchfrequentie. Een suboptimale werptechniek verhoogt in theorie ook het risico op UCL letsel, waarbij bepaalde werpparameters gerelateerd zijn aan hogere inwerkende krachten op de elleboog. Het integreren van lenigheid, kracht en proprioceptieve training in de trainingsroutine van een atleet zou het blessurerisico kunnen verminderen, waarbij het belang van aandacht voor preventie op de jeugdleeftijd moet worden benadrukt.

Inspanningen om UCL letsel te voorkomen omvatten de implementatie van pitch limieten en trainingsprogramma's zoals de *Thrower's Ten* en het *Pitchers Baseball Bat Training Program*. De effectiviteit van deze programma's is echter onduidelijk. Het *Yokohama-9-programma* uit Japan heeft aangetoond het aantal elleboogblessures te verminderen. Uitdagingen in het kader van blessurepreventie blijven bestaan vanwege een gebrek aan bewustzijn van risicofactoren en navolging van aanbevelingen onder spelers en coaches en de onvoorspelbare aard van UCL letsel. Culturele factoren en het streven naar een professionele honkbal carrière dragen ook bij aan een slechte naleving van richtlijnen voor werpbelasting, waarbij de noodzaak van effectieve interventies om de UCL tijdens het werpen te beschermen ondergesneeuwd raken.

Traditionele benaderingen voor blessurepreventie, gericht op lineaire causaliteit en geïsoleerde risicofactoren, zien de dynamische en veelzijdige aard van sportblessures gemakkelijk over het hoofd. De *complexe systeem benadering*, waarbij wordt uitgegaan van niet-lineaire interacties tussen risicofactoren, kan de mogelijkheid om effectieve preventiestrategieën te ontwikkelen verbeteren. Techniektraining van sporters en atleten moet gezonde variabiliteit in beweging en zelforganisatie van het lichaam omarmen, waarbij er ruimte voor verkenning en aanpassingen aan individuele beperkingen mogelijk moet zijn. Trainingsmethoden volgens deze benadering richten zich op het verbeteren van de robuustheid van de sporter - het weerbaarder maken tegen de tegen belasting in een onvoorspelbare omgeving. Er zijn echter langetermijnstudies nodig om de effectiviteit van deze 'nieuwe' trainingsmethoden te objectiveren en veilige trainingsvariabiliteit voor specifieke atletische vaardigheden vast te stellen.

Bovenhandse sportactiviteiten die gekenmerkt worden door repetitieve en krachtige acties van de bovenste extremiteit, vormen een risico voor UCL letsel. De aard van deze activiteiten varieert aanzienlijk tussen verschillende sporten, wat van invloed is op de kans op elleboogblessures. Pitchen in honkbal valt op vanwege de inherente herhaling en focus op hoge snelheid, waardoor honkbal pitchers bijzonder kwetsbaar zijn voor blessures van de UCL. Daarentegen bieden de opzet van andere bovenhandse sporten, zoals American football, handbal en volleybal, meer ruimte voor variatie in beweging en lagere krachten op de elleboog, wat het risico op UCL letsel vermindert. Professioneel tennis, met name het serveren, vertoont repetitieve bewegingen die in omvang vergelijkbaar zijn met pitchen, met een vergelijkbaar aantal opslagen per wedstrijd. De literatuur over tennis-specifieke UCL blessures is echter beperkt, waarbij de meeste studies verwijzen naar eerdere studies uit het honkbal. Desalniettemin kan UCL letsel bij niet-honkballers verkeerd worden gediagnosticeerd of niet worden herkend, wat leidt tot onnodige vertraging van adequate behandeling.

Ontwikkelingen in de biomechanica en beeldvormende modaliteiten zullen aanknopingspunten bieden voor het begrijpen en voorkomen van ernstig UCL letsel bij bovenhandse sporters. Biomechanische bewegingsregistratie met draagbare sensoren en biofeedback kunnen nieuwe trainingsmethoden die zich richten op het vergroten van de robuustheid van atleten ondersteunen. Hoogwaardige MRI en echografie maken vroege detectie van veranderingen van de UCL mogelijk, terwijl biologische en regeneratieve therapieën potentie hebben op het domein van (secundaire) blessurepreventie en vroege behandeling. Verder onderzoek is nodig om intrinsieke (risico)factoren zoals individuele variabiliteit in botmorfologie en de effectiviteit van nieuwe therapieën voor de preventie en behandeling van UCL letsel in kaart te brengen.

Dankwoord

Deze promotie begon in zekere zin op een regenachtige dag in 2013 met een gesprek in *De Blaffende Vis* in de Jordaan. Nu, meer dan tien jaar later, rond ik mijn promotie af. Ik kijk met trots terug en dank iedereen die direct of indirect, gemerkt of ongemerkt, en bedoeld of onbedoeld heeft geholpen bij het volbrengen van deze PhD.

If you can dream—and not make dreams your master;
If you can think—and not make thoughts your aim;
If you can meet with Triumph and Disaster
And treat those two impostors just the same;

from: "If"
by Rudyard Kipling, 1910

Beste Denise, professor Eygendaal. Via Michel kwam ik bij je terecht en ik had me geen fijnere promotor kunnen wensen. Je positieve benadering en oplossingsgerichtheid zijn een belangrijke factor geweest in het slagen van dit boekje. Na ieder telefoontje om de zaken door te spreken zag ik licht aan het einde van de tunnel, of - beter nog - bleek er helemaal geen tunnel te zijn. Dank voor je begeleiding, steun en vertrouwen.

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Dear Luke, Dr. Oh. After being formally introduced to you by Rens Bexkens in the summer of '16, you introduced me to the thrower's elbow and the UCL issue. It has been a wonderful subject to delve into. I am sure it has not been easy to fit 'the Dutch guys' in your busy schedule, but I sincerely thank you for the opportunities you have given me. Living in Somerville and working at MHG's Sports Medicine Center in Boston has been a life-changing experience. I wish you and your family all the best.

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Mark Nazal, Jakob Ackermann, Ali Parsa & Giovanna Medina - After my Dutch colleagues left, you filled the gap. You all had my back and I sincerily thank you for it. Mark, you have been my US cheerleader. Jakob, MD PhD without a PhD, I wish you love (your career won't be a problem). Hope dies last, my friend. Ali, you are truly the nicest person I've ever met. Giovanna, you are a winner. We'll meet again.

Dear Luna & Nicola, Somerville friends. Arriving at 56 Craigie Street on your secret wedding day... and staying at your place with Renato and Youde Ma really

* De *tush push* is een controversiele manier om de quarterback in het American football door middel van een duw van achteren over de touchdown line te drijven. De tactiek werd in 2023 geperfectioneerd door de Philadelphia Eagles en wordt ook wel de 'Brotherly Shove' genoemd, naar de bijnaam van de stad Philadelphia (City of Brotherly Love).

made for the best start of our time in the States. Thinking back to our weekly dinners at Craigie and Heath and restaurants throughout Boston brings back feelings of great happiness. Boston did not feel the same after you left. I am grateful for our ongoing friendship. Although we will probably live far apart the rest of our lives, I am sure we will keep finding eachother.

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They fuck you up, your mum and dad.
They may not mean to, but they do.
They fill you with the faults they had
And add some extra, just for you.

from: "This Be The Verse"
by Philip Larkin, 1971

En als allerlaatste,

Guusje.

Ik zie je nog - verderop aan een statafel op Olympos. Van de Korte Lauwer naar de Adriaen Beyer, van de Nieuwegracht naar Heath Street, van de Van Musschenbroek naar de Hazenkampseweg. Dank voor dit mooie avontuur.

You are everything.

Fenway Park, 8 Oct, 2017 • Houston Astros @ Boston Red Sox ALDS Game 3 (10-3)


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50
16

Portfolio

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Chapter 13. Medial ulnar collateral ligament insufficiency in athletes.
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GRANTS AND AWARDS

Kilfoyle Award for 2nd Best Resident/Fellow Presentation
New Engeland Orthopaedic Society 2019 Spring Meeting, Woodstock, VT

MGH Research Stipend 2018
Sports Medicine Center, Massachusetts General Hospital, Boston, MA

Anna Fonds Reisbeurs 2017
Anna Fonds | NOREF

PhD Onderzoeksleningen 2017
Stichting Vreedefonds; Fundatie van Renswoude

Hendrik Muller PhD Onderzoeksbeurs 2016
Hendrik Muller Fonds

AUF Spinoza Beurs 2015
Amsterdams Universiteitsfonds

KNAW Van Walree Beurs 2014
Koninklijke Nederlandse Akademie voor Wetenschappen

Traumaplatform Prijs 2014
Stichting Traumaplatform, Amsterdam

Nutrition & Sports
Stichting Opleidingen in de Sportgezondheidszorg (SBOS)
2-Day course: February 10 & 11, 2022

Sports Physiotherapy
Stichting Opleidingen in de Sportgezondheidszorg (SBOS)
1-Day course: September 2021

Clinical Epidemiology
Stichting Opleidingen in de Sportgezondheidszorg (SBOS)
1-Day course: April 2021

Nutrition, Exercise and Sports
Wageningen University / edX (e-course); 2019

Data Science: R Basics
HarvardX / edX (e-course); 2019

Certificate in Applied Biostatistics
Harvard Catalyst Education Program | Course director: dr. Brian Healy
Weekly e-lectures and practicum exercises using STATA statistical software
September 18 - July 1, 2018

Sports and the University
Lagunita, Stanford University Online Courses | Humanities Sciences; 2018

Effectively Communicating Research
Harvard Catalyst Education Program | Harvard Medical School, Boston, MA
2-Day course: October 31 - November 1, 2017

Maximizing the Mentee-Mentor Relationship
Harvard Catalyst Education Program | Simmons College, Boston, MA
2-Day course: June 15 & 16, 2017

America's Poverty and Inequality Course
Lagunita, Stanford University Online Courses | Humanities Sciences; 2017

2023 Cardiology Academy Week
Nijmegen, The Netherlands | Podium (invited speaker)

2023 2nd Voetbalmedisch symposium CWZ-N.E.C.
Nijmegen, The Netherlands | Podium (invited speaker)

2023 VOCA congress
Amsterdam, The Netherlands | Podium (invited speaker)

2020 American Academy of Orthopaedic Surgeons Annual Meeting
Orlando, Florida, USA | Podium; cancelled due to COVID-19 pandemic

2019 14th International Congress of Shoulder and Elbow Surgery (ICSES)
Buenos Aires, Argentina | ePoster

2019 Nederlandse Vereniging voor Arthroscopie (NVA) jaarcongres
Nieuwegein, The Netherlands | Podium

2019 New England Orthopaedic Society (NEOS) Spring Meeting
Woodstock, Vermont, USA | Podium

2017 28th Richard J. Smith Lectoraat at Massachusetts General Hospital
Boston, Massachusetts, USA | Podium

2014 Traumadagen
Amsterdam, The Netherlands | Podium

2014 15th EFORT Annual Congress
Londen, UK | Podium & Poster

2013 Symposium Experimenteel Onderzoek Heelkundige Specialismen
Maastricht, The Netherlands | Poster

108 Heath Street (Unit 2), Somerville, MA 02145

Curriculum Vitae

Rik Jozef Molenaars werd op 12 september 1989 geboren in Eindhoven. Na het behalen van zijn VWO diploma aan het Pleincollege Van Maerlant in 2007 begon hij aan de versnelde opleiding fysiotherapie aan de Hogeschool Utrecht. In diezelfde periode maakte hij de overstap van de A-jeugd van RPC Eindhoven naar de heren-selectie van de Utrechtse studentenvoetbalvereniging Odysseus '91, waar hij 7 seizoenen zou spelen. Met een bachelor fysiotherapie en pre-master fysiotherapiewetenschappen op zak en het doel om sportarts te worden, werd hij in 2010 via de decentrale selectie toegelaten tot de opleiding geneeskunde in het Academisch Medisch Centrum (AMC) aan de Universiteit van Amsterdam. Onder de bevlogen supervisie van (prof.) dr. Job Doornberg deed hij in de wachttijd voor zijn coschappen een wetenschappelijke stage op de afdeling orthopedie van het AMC, waar zijn interesse voor wetenschappelijk onderzoek werd aangewakkerd.

Na het in ontvangst nemen van zijn artsenbul in 2017 verruilde Rik, samen met Guusje, de Nieuwegracht 33 in Utrecht voor 108 Heath Street in Somerville, waar hij gesteund door verschillende onderzoeksbeurzen gedurende twee jaar aan zijn PhD werkte in het Massachusetts General Hospital. Zijn werkzaamheden in het Sports Medicine Center van MGH/Harvard Medical School – onder begeleiding van dr. Luke Oh, prof. dr. Van den Bekerom (OLVG en Amsterdam UMC) en prof. dr. Eygendaal (Amphia ziekenhuis, Erasmus MC) – vormen de basis van deze dissertatie.

Op 20 juli 2018 trouwden Rik en Guusje in Cambridge City Hall en op 13 oktober 2018 werd hun eerste dochter geboren in Brigham & Women's Hospital in Boston. In juni 2019 keerde Rik met zijn gezin terug naar Utrecht en werd na een periode als ANIOS cardiologie in het Jeroen Bosch Ziekenhuis toegelaten tot de opleiding sportgeneeskunde.

Rik is sportarts in opleiding in het Canisius-Wilhelmina Ziekenhuis en clubarts bij de N.E.C. Voetbalacademie en woont met Guusje en dochters Eddie en Sjuul in de Hazenkamp in Nijmegen.