EXAMINING THE RELATIONSHIPS BETWEEN SHOULDER AND ELBOW SOFT-TISSUE PROPERTIES, THROWING MECHANICS, AND RANGE OF MOTION IN ADULT BASEBALL PITCHERS

by

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Overhead throwing places extremely high loads on soft-tissue structures of the shoulder and elbow, causing pitchers to be injured at an alarming rate. Most researchers believe soft-tissue injuries in pitchers are acute manifestations of chronic microtrauma as a result of repetitive near-maximal loading. While specific mechanical factors and range of motion deficits have been reported as predictors of future injury risk in pitchers, it is unknown how the properties of the tissues themselves are changing in relation to these factors. **The primary purposes of this research were to examine the structural and material properties of critical soft-tissue structures in the arms of adult baseball pitchers and to evaluate relationships between those properties and previously identified mechanical and range of motion injury risk factors.** The reliability of a novel shearwave ultrasound elastography imaging protocol was developed and tested for inter- and intra-rater reliability and found to be reliable for 10/11 tissue properties. After the completion of protocol design, 26 healthy and currently competitive baseball pitchers participated in bilateral imaging, bilateral range of motion evaluations, and full-body 3D motion capture of the pitching motion. Significant bilateral differences were found in 7 out of the 11 tissue properties examined, displaying the effect pitching on the throwing arm. Pitchers with elevated shoulder kinetics during the pitching motion displayed decreased material stiffness of shoulder tendons, specifically the supraspinatus, infraspinatus, and biceps brachii long head. There were not any relationships between elevated elbow kinetic variables and the properties of the medial elbow or UCL. Pitchers with GIRD and TRM were found to have significantly stiffer supraspinatus muscle than pitchers without GIRD or TRM deficits and a significant interaction was found between Arm and GIRD for supraspinatus tendon stiffness. Additionally, interactions between Arm and TRM and Arm and shoulder flexion deficit were found for UCL stiffness. This research expands the field's understanding of the specific tissue changes occurring in pitchers with previously described injury risk factors. This research provides biological evidence strengthening the argument that soft-tissue shoulder injuries in baseball pitchers result from chronic microtrauma produced by repetitive exposure to extreme loads during the baseball pitching motion.

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by

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LIST OF SYMBOLS / ABBREVIATIONS

BBLH	Biceps brachii long head
kPa	kilopascal
mm	millimeter
SWE	Shearwave Ultrasound Elastography
UCL	Ulnar collateral ligament
UH Joint Space	Ulnohumeral joint space

CHAPTER 1: INTRODUCTION AND REVIEW OF RELEVANT LITERATURE

The overhead throwing motion commonly used in baseball pitching places extremely large loads on the structures of the throwing shoulder and elbow, and injuries to the throwing arms of pitchers are among the most frequent and costly injuries in baseball players. Prior research has shown that many of the critical soft-tissue structures in the throwing arm undergo changes in structural properties (length, thickness, etc.), presumably resulting from the high loads placed on them during the throwing motion, however these changes have not been found to be predictors of future injury risk in baseball pitchers. Recent research has begun to examine the material stiffness of soft-tissues in the throwing arms of baseball pitchers, in an effort to further understand the effect of baseball pitching on soft-tissue structures in the throwing arm, however these initial studies have not examined relationships between material properties and previously identified injury risk factors. **There is still a large need for a greater understanding of the changes that occur in the material stiffness of critical soft-tissue structures as a result of baseball pitching, and to what extent these changes are related to previously identified injury risk factors, such as the kinetics and kinematics of an individual's throwing motion, and bilateral shoulder range of motion deficits.**

Rise in Injury Incidence in Baseball Pitchers

Recent data shows that professional baseball players spend a combined 25,000+ days on the injured list, costing over $420 million annually, with the two most common injury regions being the "shoulder" and "arm/elbow" (Conte et al., 2015). Between 1998 and 2015, the annual number of shoulder injuries shows a significant decline while remaining the most commonly injured region of the body, however the number of elbow injuries annually significantly increased over that same time span (Conte et al., 2016). At the Major League level, the highest level of competitive baseball, upper extremity injuries account for over 51% of all injuries to all players. Looking specifically at arm injuries, pitchers had a greater incidence rate (34% higher), experienced a greater proportion of injuries to their upper extremities (34.9% higher), and made up a greater proportion of days spent on the disabled list (24.8% greater) compared to fielders (Posner et al., 2011). The greatest number of upper extremity injures have been shown to occur in the beginning of each season (March-April) (Ciccotti et al., 2017; Fares et al., 2020b, 2020a; Posner et al., 2011).

While the number of injuries annually and length of time out of competition for shoulder injuries had a slight decline from 1998 to 2015, the prevalence and severity of elbow injuries in Major League Baseball players increased (Conte et al., 2016). The most common, and most severe, elbow injury in baseball pitchers is an injury to the ulnar collateral ligament (UCL) in the medial elbow, and the incidence of UCL injuries at all levels of competitive baseball has continued to increase over the last 20 years (Conte et al., 2016, 2015; Fleisig, 2015; Petty et al., 2004; Posner et al., 2011; Rothermich et al., 2017). A widespread survey of professional baseball players in 2012 found that 16% of all professional pitchers, and 25% of Major League pitchers at the time had undergone at least one UCL reconstruction (Conte et al., 2015). Between 2010 and 2016, 32% of all elbow injuries that caused a Major League Baseball player to spend time on the Disabled List resulted in that player undergoing surgery on their elbow (Fares et al., 2020b). Similar patterns are seen when Minor League Baseball players are included in epidemiological reviews. Examining 3185 elbow injuries in Major League and Minor League players, 40% of all players with elbow injuries were pitchers, 34% of pitchers with an elbow injury required surgery, and more than half of all elbow surgeries were targeting ligament injuries in professional baseball players (Ciccotti et al., 2017). In Major League players, the beginning of the season (March) had the greatest number of elbow injuries and the greatest number of ligament injuries, while July had the most elbow injuries and ligament injuries in Minor League players (Ciccotti et al., 2017).

Between 1998 and 2015, shoulder injuries represented over 20% of the injuries that placed a professional baseball player on the Disabled List, accounting for 26.2% of the total days spent on the Disabled List (Conte et al., 2016). In a more recent examination of all injuries that placed Major League Baseball players on the “Disabled List” between 2011 and 2016, shoulder injuries were found to be the most prevalent (17%), followed by elbow injuries (14 %). More than 25% of shoulder injuries were due to inflammation, making it the most common injury type, followed by strains (24%) and tendinitis (13%). Almost 10% of shoulder injuries that resulted in a player being placed on the Disabled List required that player to undergo some type of shoulder surgery (Fares et al., 2020a). Pitchers represented 77% of the players with shoulder injuries and the most common time for shoulder injuries to be reported was the month of April. 80% of all shoulder injuries that required surgery occurred during the months of March and April (Fares et al., 2020a).

Even with an increased awareness and focus on preventing such throwing injuries, the incidence of injury, number of days missed due to injury, and cost of throwing injuries (especially to the ulnar collateral ligament) have been increasing in adolescent, collegiate, and professional levels over the past 20 years (Conte et al., 2015; Fleisig, 2015; Posner et al., 2011). It is widely reported that there is a strong relationship between the amount of pitching an individual performs and their injury risk, however this is largely only true in youth and adolescent baseball players (Fleisig and Andrews, 2012; Lyman et al., 2001; Mautner and Blazuk, 2015; Yang et al., 2014). In professional pitchers, two studies have found that no cumulative work metric is a significant predictor for future injury (Karakolis et al., 2015, 2013; Saltzman et al., 2018). This continued dramatic rise in pitching injuries has led to subsequent increased in the number of research groups in and out of professional baseball focused on trying to better understand these injuries and how to avoid them (Wake Forest University Athletics, 2019; Giler, 2017). Despite the increased efforts of many professional organizations and research labs, the continued rise in injury rates in baseball pitchers highlights the importance of continued research focused on understanding how best to decrease the frequency and severity of these injuries.

Biomechanics of the Baseball Pitching Motion

While there are a variety individual styles and manifestations of it, the overhead throwing motion is the most commonly used baseball pitching style. This throwing motion can be broken down into six phases of the Windup, Stride, Arm Cocking, Arm Acceleration, Arm Deceleration, and the Follow-Through, (Figure 1) (Chalmers et al., 2017; Dillman et al., 1993; Fleisig et al., 1995; Fortenbaugh et al., 2009). The description that follows will describe each phase, a greater emphasis will be placed on the arm cocking and arm deceleration phases, as they have been described as the two critical phases of the overhead pitching motion when the structures of the shoulder and elbow have the greatest loads placed on them and are at the greatest risk for musculoskeletal injury (Fleisig et al., 1995).

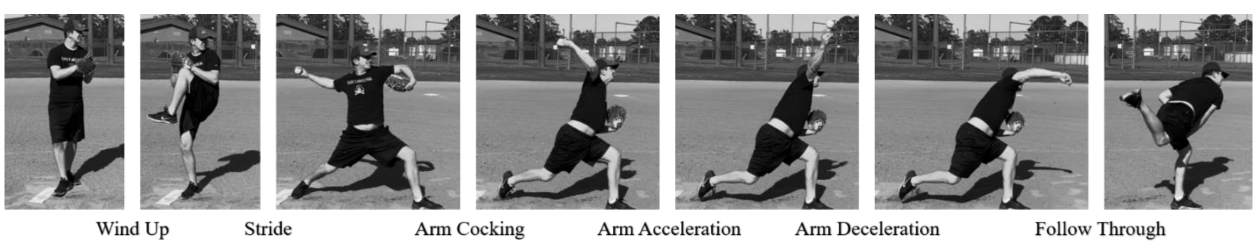


Figure 1. Phases of the overhead throwing motion used in baseball pitching.

The pitching motion begins with the wind-up phase as the pitcher makes their initial movement to begin the motion. This phase includes the lifting of the front leg and ends when the front leg has reached its peak height before accelerating towards home plate and as the throwing hand separates from the glove hand. During the wind-up phase, the pitcher is moving the body to a more powerful position, balancing over his rear leg with his throwing elbow in a flexed position, and there is very little movement at the elbow.

The pitching motion continues with the stride phase, beginning as the lead leg starts moving towards home plate and the arms continue to separate, and concluding when the lead foot makes contact with the mound. Potential concerns during this phase are the lead foot landing in an excessively toe-out position as a result of external rotation at the hip greater than 90°, or the lead foot landing while the hip of the lead leg is hyperextended. In either of these scenarios, there is the possibility that the pelvis will rotate too early in the pitching motion, causing the torso and shoulder girdle to begin their forward rotation while the throwing arm is still is still moving slightly backwards and preparing to begin its forward motion. This opposition of rotation caused by a deviation from proper foot and pelvis mechanics during the stride phase will produce increased forces in the anterior shoulder and medial elbow (Fortenbaugh et al., 2009). Additionally, if there is insufficient or excessive external rotation of the shoulder at the end of the stride phase, the throwing arm may lag behind the rest of the body and the shoulder girdle. Increased valgus forces at the elbow resulting from either improper positioning of the stride foot or from a deviation from proper external rotation of the shoulder will place additional stress on the UCL in the subsequent phases of the pitching motion (Fortenbaugh et al., 2009).

Following the stride is the first critical phase of the pitching motion, the arm cocking phase, ending when the upper arm of the throwing arm has reached a position of maximal external rotation. Large forces and torques are seen in both the shoulder and elbow as the arm cocking phase progresses. During this phase of the pitching motion, an internal rotation torque of 67 ± 11 Nm, a horizontal adduction torque of 87 ± 23 Nm and an abduction torque of 44 ± 17 Nm are generated at the shoulder. Likewise, 310 ± 100 N of anterior force, 250 ± 80 N of superior shear force, and 480 ± 130 N of compressive force were produced in the shoulder (Fleisig et al., 1995). After the lead foot makes contact with the mound, the trunk and pelvis begin rotating towards home plate creating a minor flexion torque at the elbow of 0-32 Nm (Fleisig et al., 1995; Loftice et al., 2004). The late cocking phase is often considered the period of the pitching motion in which the greatest stress is placed on the UCL as it goes through an abrupt, tremendous increase in valgus stress (Ciccotti et al., 2014; Fleisig et al., 1995; Loftice et al., 2004; Nazarian et al., 2003). In the latter part of the arm cocking phase, the elbow is flexed 95° ± 10° and the glenohumeral joint is externally rotated 165° ± 11°, abducted 94° ± 21°, and horizontally adducted 11° ± 11°, which results in the generation of a large valgus torque onto the upper arm at the elbow (Fleisig et al., 1995; Loftice et al., 2004). This valgus torque is resisted through the generation of a varus torque of 64 ± 12 Nm on the forearm just prior to the maximum external rotation of the shoulder (Loftice et al., 2004; Werner et al., 1993). Additionally, 300 ± 60 N of medial force, 160 ± 80 N of anterior force, and 270 ± 120 N of compressive force was produced on the elbow towards the end of the arm cocking phase (Fleisig et al., 1995). The generation of the large external valgus torques and accompanying varus torques in the elbow during the late stages of the cocking phase perhaps makes the UCL most susceptible to injury during this portion of the pitching motion.

One potential risk factor for pitching injuries during the arm cocking phase is increased horizontal adduction of the shoulder. Anterior shoulder force, medial elbow force, and horizontal adduction shoulder torque all increase in pitchers who excessively adduct the shoulder horizontally during the arm cocking phase (Fortenbaugh et al., 2009). This is often described in lay terms as a pitcher "leading with the elbow." Such a pattern is often seen in pitchers with a compromised UCL as it lowers the varus torque produced in the elbow, and subsequently lowers the strain on the UCL (Andrews et al., 2001; Fortenbaugh et al., 2009; Levin et al., 2004). However, this alteration of pitching mechanics places additional stress on the shoulder joint and may be one explanation of shoulder injuries in pitchers with previous elbow injuries (Fortenbaugh et al., 2009).

Next, the arm acceleration phase, which is the shortest, most dynamic, and most intense phase of the baseball pitching motion. This phase continues from maximum shoulder external rotation as the arm accelerates forward and concludes and the time the ball is released from the hand. Throughout the arm acceleration phase, the elbow goes through extension as the forearm swings out to the side of the pitcher and the trunk continues to rotate forward (Fortenbaugh et al., 2009; Werner et al., 1993). The elbow reaches a maximum extension velocity between 2100°/s and 2700°/s, which is most likely due to the rotary actions of several body segments and not solely because of the elbow extensors (Fortenbaugh et al., 2009). Throughout this rapid extension at the elbow, centrifugal force applies a large distraction force on the elbow joint which is countered by a compressive force of 800-1000N applied by the triceps, wrist flexors, and anconeus in order to maintain elbow integrity (Fortenbaugh et al., 2009; Werner et al., 1993). A substantial varus torque is also generated during the arm acceleration phase in order to resist valgus elbow torque and accelerate the forearm forward into the ball release (Fortenbaugh et al., 2009).

After ball release, the baseball pitching motion continues with the arm deceleration phase until the arm reaches maximum internal rotation, decelerating from its rapid forward motion and dissipating its energy through the shoulder and elbow. Regarding stress at the shoulder joint, the arm deceleration phase is described as the second critical instance in the pitching motion, after the late cocking phase (Fleisig et al., 1995). At this point, a peak compressive force of 1090 ± 110 N, or close to 90% of the pitcher's body weight, is seen at the shoulder in order to prevent excessive arm distraction (Fleisig et al., 1995; Werner et al., 1993). Deceleration at the elbow occurs as a result of a flexor torque prior to full extension created by an eccentric contraction of the biceps brachii (Werner et al., 1993). The elbow is flexed only 25° ± 10° while the arm is externally rotated 64° ± 35°, abducted 93° ± 10°, and horizontally adducted 6° ± 8° at the shoulder during this phase of the pitching motion. Overall, the pitcher's throwing shoulder is under much greater stress during the arm deceleration phase in comparison to the medial elbow and the UCL.

The final phase of the pitching motion is the follow-through, beginning with the arm in maximum internal rotation and finishing when the pitcher reaches a balanced fielding position (Dillman et al., 1993; Fleisig et al., 1995; Fortenbaugh et al., 2009; Loftice et al., 2004; Werner et al., 1993). The motion of the larger body parts including the trunk and legs continues to dissipate the energy from the throwing arm while the elbow and shoulder return to a more comfortable position in relationship to the rest of the body (Fleisig et al., 1995; Fortenbaugh et al., 2009; Werner et al., 1993).

Baseball Pitching Injury Risk Factors

As discussed previously, the number one injury risk factor in youth and adolescent baseball pitchers is overuse, however this specific risk factor relationship is not as conclusive in adult pitchers (Fleisig et al., 2011; Karakolis et al., 2015, 2013; Lyman et al., 2001; Saltzman et al., 2018; Yang et al., 2014). This can be measured as the amount of pitches or innings thrown in a single game, season, or year, as well as the number of games played in a year, the number of months played in a single year without adequate rest and recovery time, and playing for multiple teams in a single season (Lyman et al., 2001; Major League Baseball, 2020; Wilk et al., 2011; Yang et al., 2014). Recent research has identified moderate relationships between increasing workload per week and increasing self-reported arm pain as the season progresses in collegiate pitchers, however the authors again state that measuring metrics such as pitch count may still not be the most effective measurement of workload for predicting injuries in pitchers (Lazu et al., 2019). In adult pitchers however, both kinetic and kinematic factors in the overhead throwing motion and range of motion deficits in the throwing arm have been indicated as injury risk factors (Aguinaldo and Chambers, 2009; Anz et al., 2010; Wilk et al., 2015, 2011, 2004).

Examining kinetic and kinematic factors of the pitching motion in relation to adult pitching injuries, the literature lacks large-scale conclusive prospective injury findings, perhaps due to the inherent difficulties of prospective injury research. In one prospective injury study on a sample of 25 pitchers, there was a near-significant trend between pitchers who remained healthy and those that suffered an elbow injury in the following three years for elbow valgus torque and shoulder external rotation torque throughout the pitching motion. At the instance of maximum shoulder external rotation, pitchers that remined healthy demonstrated decreased elbow valgus torque and increased shoulder external rotation torque compared to pitchers suffered a subsequent elbow injury (Anz et al., 2010). Recent research also suggests that improper timing of trunk rotation correlates higher levels of peak elbow valgus torque, shoulder proximal force, and shoulder external rotation angle, and thus may be related to injury (Aguinaldo et al., 2007; Aguinaldo and Chambers, 2009; Chalmers et al., 2017; Oyama et al., 2014). Much of the other literature describing the potential (but not definitive) relationships between the pitching motion and injury risk seek to better understand specific kinematic variables or sequences that are related to elevated torques and forces on the throwing arm, as those high loads on the shoulder and elbow are ultimately believed to be the cause of many common injuries in baseball pitchers. For example, several of the several of the seminal papers describing the baseball pitching motion and injury risk focus on the mechanics related to elevated kinetics rather than to injury data in prospective research, including Escamilla et al., 1998; Fleisig et al., 1995; and Werner et al., 1993. The potential effects of those loads on the specific structures of the shoulder and elbow are discussed in the next section, *Soft-Tissue Loading during the Baseball Pitching Motion*.

It is well reported that adult baseball pitchers present with altered range of motion of the throwing shoulder as a result of repeated exposure to the high torques created during the pitching motion. Bilateral shoulder range of motion deficits where the throwing arm has a decreased range of motion compared to the non-throwing arm have been linked to pitching injuries in both elbow and shoulder of the throwing arm. Previous research consistently reports increased shoulder external rotation (> 5°) and decreased shoulder internal rotation (> 10°) in their throwing arm compared to their non-throwing arm (Camp et al., 2017; Pexa et al., 2019; Wilk et al., 2015, 2011, 2004).

A loss of internal rotation in the throwing shoulder of 20° compared to the non-throwing arm has been termed glenohumeral internal rotation deficit (GIRD) and was initially suggested to be the cause of specific shoulder injuries in baseball pitchers (Burkhart et al., 2003). However, further research has suggested that GIRD may predict some injury, other research has found examining solely loss internal rotation not to be predictive of future injury. The changes in the rotational capability of the shoulder appear to be a posterior shift in the location of the functional range of motion rather than a pure loss of mobility, and pitchers often display a total rotational range of motion (TRM) in their throwing shoulder within 5° of their non-throwing arm (Wilk et al., 2004). This increase in external rotation may be a protective adaptation as increases in external rotation are associated with decreased peak stresses at both the shoulder and elbow during pitching (Hurd and Kaufman, 2012). In a prospective case series using ROM measurements taken during three pre-season training periods, pitchers with bilateral deficits greater than 5° of TRM, they are 2.5 times more likely to suffer an injury to their throwing shoulder in the following baseball season (Wilk et al., 2011). Shoulder range of motion deficits have also been linked to increased risk of elbow injuries in baseball pitchers. Shoulder flexion deficits greater than 5° compared to the non-throwing arm were 2.83 times more likely to suffer an elbow injury, and when evaluated as continuous variables, the odds ratio of injury was 1.09 with for each degree of decreasing shoulder flexion and 1.07 for each degree that bilateral external rotation deficit increased (Camp et al., 2017).

Soft-Tissue Loading during the Baseball Pitching Motion

Most baseball researchers agree on the theory that overuse injuries in baseball pitchers are a product of accumulated microtrauma resulting from the large forces and torques exerted at the shoulder and elbow during the overhead throwing motion (Andrews et al., 1985; Andrews and Angelo, 1988; Buffi et al., 2015; Burkhart et al., 2003; Fleisig et al., 1995; Park et al., 2002a; Wilk et al., 2004). The repetitive loading of soft-tissue structures, while sub-maximal, has the potential to lead to chronic breakdown in tissue and eventual injury. Cyclic loading has shown the potential to cause fatigue failure at high, but sub-maximal, loads in collagenous structures such as tendon and ligaments (Thornton et al., 2007; Wojtys et al., 2016). In ligaments, repetitive sub-maximal loading which leads to scarring can alter the creep properties of the tissues and it is known that the combination of loading magnitude and rest intervals has significant effects on the physiological response of muscle microtrauma (Gao Smith and Gallagher, 2015; Thornton et al., 2000). It is in these times, the arm-cocking and arm deceleration phases, during which the soft-tissue structures of the shoulder and elbow of the throwing arm are under the highest loads and thus believed to be at the greatest risk of injury (Fleisig et al., 1995; Park et al., 2002a). Although the magnitude of loading is described as a concern, it is the repetitive exposure to such high loads that makes two specific time periods during baseball pitching motion specific timepoints of concern.

Near the end of the arm-cocking phase, the structures of the elbow must resist a tremendous external valgus load and the structures of the shoulder also produce a large internal rotation torque and a large anterior force (Fleisig et al., 1995). The magnitude of the varus torque generated in the medial elbow and the contribution of the UCL to that varus torque places the UCL near its maximum resistive capacity during this phase of the pitching motion (Fleisig et al., 1995; Morrey and An, 1983; Werner et al., 1993). Several soft-tissue structures in the shoulder are also subject to large loads during the arm-cocking phase. The muscles of the rotator cuff are also active during the arm-cocking phase, with the infraspinatus and teres minor being largely responsible for the extreme degree of external rotation of the humerus (Glousman, 1993; Park et al., 2002a). The stress caused by maximal shoulder external rotation and horizontal abduction at the shoulder during the late arm-cocking phase can cause the static stabilizers (ligamentous tissues) of the anterior shoulder to sustain soft-tissue microtrauma. This microtrauma from repetitive loading of the anterior stabilizers of the shoulder can result in hyperlaxity and anterior translation of the humerus causing microtears in anterior shoulder musculature and internal impingement of the shoulder (Park et al., 2002a). Additionally, the long head of the biceps brachii contributes to anterior stability of the glenohumeral joint during the late arm-cocking phase by limiting anterior translation of the humeral head and acting as a restraint against excess external rotation (Park et al., 2002a). The repetitive loading and subsequent microtrauma to the long head of the biceps brachii during the arm-cocking phase has been suggested to play a role in anterior instability of the shoulder and may be related to the incidence of superior labrum tears from superior to anterior, or SLAP tears (Andrews et al., 1985; Burkhart et al., 2003). Tendinitis in the long head of the biceps brachii may also result from repetitive overriding of the tendon over the lesser tuberosity during external rotation abduction in the arm-cocking phase (Zarins and Rowe, 1984).

The second critical period is when the arm is decelerating after releasing the ball. During this time the structures of the posterior shoulder must resist an extremely large distractive force generated by the arm’s forward momentum (Fleisig et al., 1995; Park et al., 2002b). The musculature of the posterior shoulder, including the supraspinatus and infraspinatus, are susceptible to tensile failure and injury at this point in the motion as they must act to resist glenohumeral distraction and horizontal shoulder adduction (Andrews and Angelo, 1988; Fleisig et al., 1995; Park et al., 2002b). If the eccentric forces being produced by posterior shoulder musculature while undergoing a large stretch and the arm continues forwards, the tendons of the rotator cuff may be overloaded and repetitive exposure to such a situation will result in accumulating microtrauma and possibly partial thickness tears to the supraspinatus or infraspinatus tendons (Meister and Andrews, 1993; Park et al., 2002b). This tensile failure in either the muscles or the tendons of the supraspinatus and infraspinatus muscles are commonly grouped in as “rotator cuff tears” (Braun et al., 2009). During this deceleration phase, supraspinatus or biceps tendinitis may also develop due to the position of the arm and need for a large compressive force at the shoulder. Pitchers with anterior instability (possibly from the high loads during the arm-cocking phase) may produce even larger loads with the biceps tendon-labrum complex (Andrews and Angelo, 1988; Fleisig et al., 1995; Glousman et al., 1988), which may lead to SLAP tears, another common shoulder injury in baseball pitchers (Braun et al., 2009; Burkhart et al., 2003).

Ultimately, the near-maximal loading of the shoulder and elbow during the arm-cocking and arm deceleration phases of the baseball pitching motion causes microtraumas in soft-tissue structures of the throwing arm such as the UCL, supraspinatus, infraspinatus and biceps tendon. These loads are sub-maximal, and a single exposure may not be dangerous by itself, but the repetitive exposure to these loads through repeated pitching bouts (perhaps without ample recovery time) has the potential to accumulate as damage. Ultimately, if the repeated exposures are stacked without ample recovery time. microtrauma accumulates and may ultimately lead to the overuse injuries that are so prevalent in pitchers.

Structural Property Adaptations in the Throwing Arms of Baseball Pitchers

The loading described above is believed to not only be the cause of overuse injuries in baseball pitchers, but also the cause of structural and material property adaptations in soft-tissue structures of the throwing arms of asymptomatic baseball pitchers (Sasaki et al., 2002). Changes in the structural properties of soft-tissues in the shoulders and elbows of baseball pitchers have been consistently reported for more than 20 years (Atanda et al., 2015; Bica et al., 2015; Ciccotti et al., 2014; Curran et al., 2016; Nazarian et al., 2003; Pexa et al., 2019).

As the primary stabilizer of the medial elbow, the UCL is responsible for resisting the majority of the external valgus torque placed on the elbow during the late arm-cocking phase of the pitching motion, and thus undergoes significant changes in the throwing arms of baseball pitchers compared to the non-throwing arm. The length of the anterior bundle of the UCL from its origin on the medial epicondyle to its insertion on the coronoid process of the ulna has been shown to be similar between arms at rest and under a valgus load, however the UCL of throwing arm undergoes a significantly greater increase in length under a valgus load compared to the non-throwing arm (Bica et al., 2015; Curran et al., 2016). Additionally, the ulnohumeral (UH) joint space of the medial elbow has been consistently reported to be similar between arms at rest, however the UH joint space is significantly larger in the throwing arm of baseball pitchers when placed under a valgus load, and the amount of change in UH joint space is significantly greater in the throwing arm (Atanda et al., 2015; Bica et al., 2015; Ciccotti et al., 2014; Curran et al., 2016; Nazarian et al., 2003; Sasaki et al., 2002). The findings of significantly greater increases in the length of the UCL and greater widening of the UH joint space under a valgus load are both indicative of increased laxity of the UCL of the throwing arm in comparison to the non-throwing arm, possibly resulting from repeated microtrauma to the ligament from the extreme loads placed on the medial elbow during the late arm-cocking stage.

Far less-extensive reporting has been done on chronic changes or bilateral differences in the structural properties of soft-tissue structures in the shoulder. One study examining the effect of a single pitching bout on the infraspinatus reported smaller cross-sectional area of the infraspinatus of the throwing arm compared to the non-throwing arm (Pexa et al., 2019). The posterior capsule of the shoulder has also been reported to be up to 30% thicker in the throwing arms of overhand throwing athletes compared to their non-throwing arms in multiple recent research studies (Astolfi et al., 2015; Takenaga et al., 2015; Vogler et al., 2019)

As striking as these differences are, it is critical to note that none of the structural changes in the soft-tissues of the shoulder or elbow have been linked to elevated risk of future injury. Dramatic widening of the ulnohumeral gap with the application of a valgus load has been described as an indicator of existing UCL injury, but not an indicator of elevated risk prior to injury occurrence, and the authors of a 10-year study of more than 350 professional baseball pitchers explicitly state that “at the present time, stress ultrasound is unable to allow a determination of the relative risk of future UCL injuries…" (Ciccotti et al., 2014). The failure of any of the bilateral differences in structural properties described above to be a strong predictor of future injury indicates the need to expand research into new directions to determine indicators of elevated injury risk.

Material Property Adaptations in the Throwing Arms of Baseball Pitchers

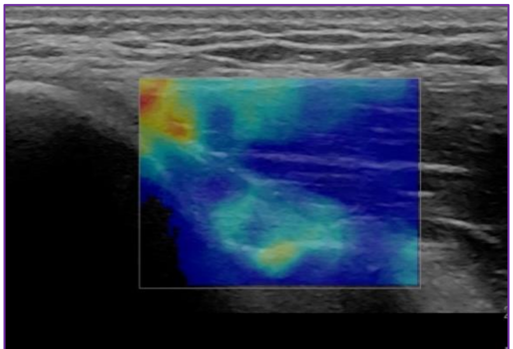


Figure 2. Shearwave Elastogram. Elastogram of the UCL showing the ligament as stiffer tissue than the flexor pronator mass above it.

The strong evidence of bilateral differences in the properties of soft-tissue structures of the shoulder and elbow in baseball pitchers, but lack of concrete relationships between structural changes and future injury risk has led recent research to explore new avenues of understanding the effect of repetitive loading on tissues, specifically by examining the material stiffness of tissues. One method for quantifying material stiffness in vivo is through the use of shearwave ultrasound elastography (SWE). In general, ultrasound elastography is the use of ultrasonic imaging to measure the degree of distortion of a specific tissue in response to an internal or external stimulus (Rosskopf et al., 2016). SWE specifically, uses conventional ultrasound waves to induce shear waves in the tissue of interest that are directed parallel to the probe face and propagate throughout the tissue. SWE then measures the velocity of the shear waves and uses those measurements in calculations to estimate tissue composition and elasticity (Drakonaki et al., 2012; Rosskopf et al., 2016). Ultimately, SWE estimates shear modulus, which can be used as a measure of material stiffness. The product of SWE is an image referred as an elastogram, which includes a color-mapped image of the tissue of interest and the ability to quantify the material stiffness of specific regions of interest in the tissue (Figure 2). SWE has been shown to be a reliable and valid method for quantifying material stiffness in a variety of musculoskeletal applications and there are preliminary reports suggesting that abnormal material stiffness of soft-tissue structures may be related to injury (Curran et al., 2016; Eby et al., 2013; Lin et al., 2018; Rosskopf et al., 2016; Salzano et al., 2015; Takenaga et al., 2015).

SWE has been used to identify changes in the material properties of the UCL and structures in the shoulders of baseball pitchers in recent years. Bilateral differences have been reported in the material stiffness of the UCL in asymptomatic collegiate baseball pitchers (Figure 3), showing significantly lower material stiffness in the throwing arm than the non-throwing arm in during a pre-season research session (Curran et al., 2016). This bilateral deficit in material stiffness of the UCL continues to suggest the presence of chronic damage experienced by the ligament during repetitive pitching, resulting in increased medial joint laxity and the structural observation of increases in ulnohumeral joint gap. Understanding the material stiffness of the UCL provides a measurement specific to the ligament, as opposed to the structural and clinical measures of the laxity of the medial elbow as a whole commonly reported in previous literature. This decreased stiffness in the throwing arm of a baseball pitcher was corroborated in a recent case report on an injured baseball pitcher (Lin et al., 2018). Although the research by Lin and colleagues reports ICC values for UCL stiffness, their data suggests that much more research and a standardization of UCL imaging is necessary. In 16

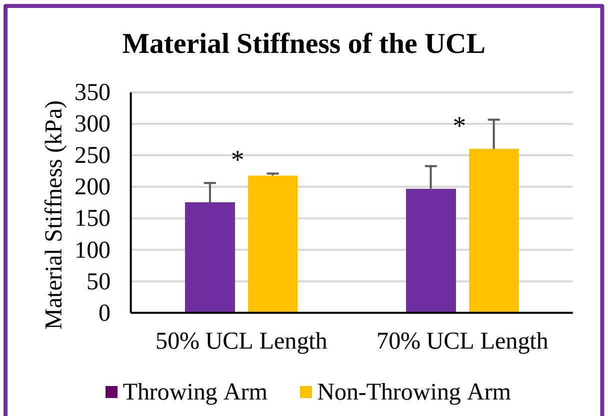


Figure 3. Bilateral Differences in UCL Material Stiffness. Material Stiffness of the UCL in collegiate baseball pitchers. The UCL in the throwing arm demonstrated significantly less material stiffness at both 50% and 70% of the length of ligament.
*$p < 0.05$

non-overhead throwers, the UCL in the throwing arm averaged approximately 110 kPa and the UCL of the non-throwing arm averaged 112 kPa. The similarity of the dominant and nondominant arms in non-throwers is a logical finding. In the case-study of a baseball pitcher *with a UCL injury*, they report UCL stiffnesses of 186.45 kPa and 879.59 kPa in the throwing and non-throwing arms respectfully. It is not clear why the non-throwing arm of an overhead throwing athlete would have a UCL that has a material stiffness 8 times greater than the throwing and non-throwing arms of non-overhead throwing adults, given other studies show differences ranging from 15-20%.

In the shoulder, the infraspinatus and teres minor of the throwing shoulder have demonstrated increased muscle stiffness in the throwing arm due to chronic muscle damage compared to the non-throwing shoulder in baseball pitchers (Yamauchi et al., 2016). This result is consistent with findings from Lacourpaille and colleagues that muscle stiffness was elevated after eccentric exercise, and that the increased stiffness could still be present 21 days later if eccentric loading occurs at longer muscle lengths (Lacourpaille et al., 2014). Material stiffness of the supraspinatus of the throwing shoulder has been reported to be greater in the throwing shoulder of adult baseball pitchers and a decrease in material stiffness of the supraspinatus in the throwing shoulder may indicate elevated risk of future pain in the throwing shoulder (Kobayashi et al., 2019). Preliminary evidence also suggests musculotendinous stiffness of the posterior rotator cuff as the primary mechanism for shoulder ROM deficits in baseball players (Bailey et al., 2015), again suggesting material property changes as the probable initial cause for the structural adaptations often reported in baseball pitchers.

These prior studies support our belief that further understanding of the changes in the material stiffness of the critical soft-tissue structures in the throwing arm is the key to decreasing injuries in baseball pitchers. However, these adaptations in the material properties of critical soft-tissue structures in the throwing arms of baseball pitchers have not been related to previously known range of motion, kinetic, or kinematic injury risk factors in baseball pitchers. Discovering relationships between previously identified injury factors and tissue properties may shed new light on the specific mechanisms of overuse injuries to pitchers. Our results may provide additional outcome measures for future prospective research studies rather than relying on the onset of significant injuries, allowing for more conclusive results identifying specific factors that are likely to cause future injuries. This new information will allow for the development of individualized preventative treatment and care, perhaps in advance of the onset of a significant injury.

The primary purposes of this research were to examine the structural and material properties of critical soft-tissue structures in the arms of adult baseball pitchers and to evaluate relationships between those properties and previously identified mechanical and range of motion injury risk factors. Understanding what changes may be occurring at the tissue level in pitchers who display previously identified injury risk factors may provide new insight into the exact mechanisms of certain injury. Also, understanding the relationships between material properties of soft-tissue structures and injury risk can prove that monitoring material stiffness of soft-tissue structures in the throwing arms of baseball pitchers is a viable proxy for understanding tissue health in these structures.

CHAPTER 2: DEVELOPMENT OF A RELIABLE IMAGING PROTOCOL FOR STRUCTURAL AND MATERIAL PROPERTY QUANTIFICATION OF SOFT-TISSUES IN THE THROWING ARM

Introduction

Ultrasonic imaging has emerged as a leading methodology for the visualization and quantification of musculoskeletal properties in athletic populations. Ultrasound's use has become widespread because it is relatively inexpensive compared to other imaging methodologies, more portable than other imaging methods, and does not have the concern of exposure to ionizing radiation (Bica et al., 2015; Yamauchi et al., 2016). Traditional ultrasound has provided tremendous insight into the structural properties of soft-tissue structures such as the length, thickness, cross-sectional area, or pennation angle. One such subset of athletes are overhead throwing athletes, who suffer soft-tissue injuries to their throwing arm at an alarming rate (Conte et al., 2016; Oberlander et al., 2000; Rothermich et al., 2017; Saw et al., 2011). Traditional B-mode ultrasound research has produced findings such as bilateral differences in UCL length and thickness, ulnohumeral (UH) gap space and the change in UH gap space under valgus load (Atanda et al., 2015; Bica et al., 2015; Ciccotti et al., 2014; Nazarian et al., 2003). While drastic changes in the delta UH joint space measurement have been reported to be linked to the presence of existing injury, the measurement UH joint space is truly a global measure of the laxity of the medial elbow and not specific to the properties of the ligament itself. <u>However, the failure of any of the structural changes reported in previous research to be a strong predictor of future injury indicates the need to expand research into new directions to determine indicators of elevated injury risk.</u>

Recent research suggests investigating changes in the material properties of soft-tissue structures of the throwing arm is a promising new direction in the quest to identify elevated injury risk and reduce the occurrence of significant injuries in the throwing arms of overhead throwers, such as baseball pitchers (Yamauchi et al., 2016). One such new methodology is shearwave ultrasound elastography (SWE). Ultrasound elastography is the use of ultrasonic imaging to measure the degree of distortion of a specific tissue in response to an internal or external stimulus (Rosskopf et al., 2016). Specifically, SWE uses conventional ultrasound waves to interact with the tissue of interest and induce shear waves that are directed horizontally and propagate throughout the tissue. SWE then measures the velocity of the shear waves and uses those measurements in calculations to estimate tissue composition and elasticity (Drakonaki et al., 2012; Rosskopf et al., 2016). Ultimately, SWE estimates shear modulus which can be used as a measure of material stiffness. The product of SWE is an image referred as an elastogram, which includes a color-mapped image of the tissue of interest. The image is also able to be processed to view the quantitative stiffness values in addition to the color map. Transitioning to visualizing and quantifying tissue properties through the use of SWE instead of traditional B-mode elastography provides the opportunity to examine material properties of soft-tissue structures in addition to all structural properties previously being evaluated, without adding significant time or risk compared to previous ultrasound techniques. Additionally, recent literature reports that SWE may have increased precision and specificity for diagnosing musculoskeletal abnormalities compared to other traditional imaging methodologies (De Zordo et al., 2009; Kapoor et al., 2010; Wu et al., 2012).

Using SWE, we previously identified bilateral differences in the material stiffness of the UCL in asymptomatic college-aged overhead athletes, showing significantly lower material stiffness in the throwing arm than the non-throwing arm in during a pre-season research session (Curran et al., 2016). This difference suggests the presence of chronic damage experienced by the ligament during repetitive overhead throwing, resulting in increased medial joint laxity and the structural observation of increases in ulnohumeral joint gap. This decreased stiffness resulting from microtrauma was corroborated in a recent case report on an injured baseball pitcher (Lin et al., 2018). Additionally, the infraspinatus and teres minor of the throwing shoulder have demonstrated increased muscle stiffness compared to the non-throwing shoulder (Yamauchi et al., 2016). Preliminary evidence also suggests musculotendinous stiffness of the posterior rotator cuff as the primary mechanism for shoulder ROM deficits in baseball players (Bailey et al., 2015), again describing material property changes as the probable initial cause for the structural adaptations often reported in overhead throwing athletes. These prior studies support our belief that a greater understanding of the changes in the material stiffness of the critical soft-tissue structures in the throwing arm is the key to decreasing injuries in overhead throwers.

To become a widely-used technique for the longitudinal tracking of soft-tissue property changes, SWE must also demonstrate adequate inter- and intra-rater reliability. SWE has been demonstrated to have very good intra-rater reliability for the measurement of teres minor and infraspinatus in a sample of overhead throwing athletes (Yamauchi et al., 2016). In the supraspinatus muscle, SWE has been shown to have good to excellent reliability for both intra- and inter-rater reliability (Rosskopf et al., 2016). One report on the reliabilty of using SWE for the measurement of UCL stiffness reported good and excellent intra-rater reliability for two separate imagers (Lin et al., 2018), while a separate recent study reported intrarater ICC values of just 0.05 (Gupta et al., 2019). These conflicting reports highlight the need for additional research into the reliabiltiy of SWE for the measurement of soft-tissue properties of the UCL. While SWE of the UCL, supraspinatus muscle and tendon and infraspinatus muscle have independently been shown to be feasible and reliable, *there has not been a comprehensive protocol including several critical* *soft-tissues of interest for medical and training professionals working with overhead athletes.* **Thus, the objective of this research was to develop and test a reliable protocol for measuring the material stiffness of soft-tissue structures in the throwing arms.** This information will be beneficial to the field by outlining a consistent, reliable method for evaluating the material properties and monitoring the health of the critical structures in an athlete's throwing arm.

We identified specific soft-tissue structures of interest prior to designing this protocol based on the most common soft-tissue injuries experienced by overhead throwing athletes. The structures are the ulnar collateral ligament (UCL), supraspinatus muscle and tendon, infraspinatus muscle and tendon, biceps brachii long head muscle and tendon.

Ulnar Collateral Ligament – The ulnar collateral ligament (UCL) is the primary stabilizer of the medial elbow during the overhead throwing motion. While the ligament is comprised of three bundles of fibers, the anterior bundle will be the focus of this research as it is most often the site of injury in baseball pitchers (Ciccotti et al., 2014). The UCL resists up to 54% of the tremendous valgus load experienced by the elbow during the most dynamic portions of the overhead throwing motion, placing it near its maximum resistive capacity (Fleisig et al., 1995; Morrey and An, 1983; Werner et al., 1993). Recent publications report that 25% of pitchers in Major League Baseball have undergone UCL reconstruction and the number of UCL injuries in pitchers has continually risen at all ages and competition levels over the past 20 years (Conte et al., 2015; Fleisig, 2015).

Supraspinatus and Infraspinatus Muscles and Tendons – In overhead throwing, the posterior shoulder muscles, including the supraspinatus and infraspinatus are highly activated during the arm deceleration phase, when they are responsible for generating large compressive forces to resist distraction, horizontal adduction and internal rotation of the shoulder at the end of the motion (Escamilla and Andrews, 2009; Fleisig et al., 1995). The magnitude of the forces these muscles are responsible for resisting may lead to tensile failure, commonly referred to as a rotator cuff tear. Drs. Andrews and Angelo, two experts in sports orthopedics, have found that most rotator cuff tears in throwers were in the mid-supraspinatus and mid-infraspinatus (Andrews and Angelo, 1988). Additionally, subacromial impingement is likely during the overhead throwing motion, in which the arm is flexed, horizontally adducted, and internally rotated, potentially resulting in tendinitis or even abrasion of the supraspinatus or infraspinatus (Escamilla and Andrews, 2009).

Biceps Brachii Long Head Muscle and Tendon (BBLH) – The biceps brachii long head muscle and tendons are structures of interest for this protocol because of their relationship to superior labrum tears from anterior to posterior, or SLAP tears. In throwing athletes, SLAP tears are thought to be repetitive overuse injuries resulting from the large force applied by the long head of the biceps during arm deceleration, tearing the labrum away from the glenoid of the shoulder (Andrews et al., 1985). The biceps brachii produces large eccentric elbow flexion torques during both the arm acceleration and deceleration phases of the overhead throwing motion, which then produces tension on the biceps tendon labrum complex (Andrews et al., 1991). Additionally, bicipital tendinitis or abrasion may occur as a result of the subacromial impingement described above (Andrews and Angelo, 1988).

Methods

We developed a comprehensive imaging protocol designed to quantify the structural and material properties of critical soft tissue structures in the throwing arm. Participants participated in two imaging sessions on two separate days within a seven-day period. During the first session, Imager 1 (CC) and Imager 2 (BD) both performed the entire protocol on the participant's throwing arm. During the second imaging session, only Imager 1 performed the imaging protocol. Imager 1 had 5 years of experience with taking sonoelastic images in musculoskeletal applications and Imager 2 had 1.5 years of experience. This sequence was designed to allow for the measurement of inter-rater reliability on Day 1, and intra-rater reliability across the two imaging sessions. Upon arriving to the Performance Optimization Lab, participants provided informed consent and had their height and weight measured. Prior to beginning the imaging protocol, participants completed a demographic and injury history questionnaire. Exclusion criteria for participation in this research included prior elbow or shoulder surgery on either arm, or a BMI ≥ 35. Participants were asked to refrain from significant upper body resistance training between imaging sessions.

All imaging was be performed using an Aixplorer (Supersonic Imagine, Aix-en-Provence, France) Ultrasound system. Images of each soft-tissue structure of interest were collected in a split screen mode, displaying B-mode (traditional ultrasound) to allow for clear identification of structural parameters of the tissues, and an elastogram (shearwave elastography colormap overlay) for the measurement of the tissue stiffness. Measurements for each outcome measure were taken from three separate images, all displaying sufficient shearwave propagation throughout the entire tissue of interest. Supraspinatus and infraspinatus muscle belly images were collected using a 10-2 Hz probe, while all other structures were imaged using an 18-5 Hz probe. All structures were imaged with the probe oriented longitudinally to the fibers of the tissue of interest

Figure 4. Participant Positioning for SWE Imaging.
A) Supraspinatus and Infraspinatus Muscle
B) Supraspinatus and Infraspinatus Tendon
C) Biceps Brachii Long Head Muscle and Tendon
D) Ulnar Collateral Ligament

The imaging protocol began with participants seated in the Crass position, with their knees at an approximately 90° angle and their hand supinated, resting on their knee (Figure 4A). The elbow was placed in line with their torso so that the elbow was flexed to 90°. Participants then shifted their arm position to the Modified Crass position (Figure 4B). The supraspinatus tendon was imaged as it crosses the head of the humerus, with the probe oriented longitudinally to the tendon fibers as well as the anterior deltoid muscle fibers. The probe was then rotated 90° and shifted posterior to image the infraspinatus tendon as it crosses the head of the humerus, oriented longitudinally to the tendon fibers and cross-sectionally to the deltoid muscles. Participants then laid supine on a treatment table for the imaging of the biceps brachii and UCL. Participants placed their hands at their side, with the forearm supinated for imaging of the biceps brachii muscle and tendon (Figure 4C). Images of the biceps brachii long head muscle belly were taken 2/3 of the length between the acromion and the anterior elbow fold, while images of the biceps brachii long head tendon were collected as the tendon passed through the bicipital groove of the head of the humerus. Participants remained laying supine on the treatment table for imaging of the UCL. They were positioned with their shoulder abducted 60-80° and their arm placed in a custom built adjustable-width arm position splint (Figure 4D). The splint is designed to maintain elbow flexion of 30° in order to unlock the olecranon from the humerus and force the soft-tissue structures of the elbow to become responsible for the joint's stability (Morrey and An, 1983). Participants held a 1-kg weight in their hand to remove slack from medial elbow structures and provide valgus loading capable of detecting bilateral differences in medial elbow laxity in overhead throwing athletes (Curran et al., 2016). UCL stiffness, UCL length, and ulnohumeral gap were measured with the forearm unsupported, allowing the weight in the hand to cause medial elbow structures to become taut and avoid attempting to measure the stiffness of the UCL in the toe region of the stress-strain curve. Ulnohumeral (UH) joint space measurements were collected in forearm-supported and valgus loaded conditions to allow for frontal plane movement and quantify the effect of loading (Bica et al., 2015).

Data Processing

All data processing was performed on the ultrasound machine, using Supersonic's proprietary processing algorithms. Tissue stiffnesses were measured by placing a circular region of interest (ROI), known as a "Q-box", within the colormap of the elastogram. The stiffness for each trial was recorded as the mean stiffness within the ROIs placed for that trial. The size of the ROI was determined and manipulated to ensure that the entire ROI was within the structure and that the material stiffness measurements were not skewed by the inclusion of neighboring soft tissue structures. Efforts were made to place the regions of interest in areas that were uniform stiffness and representative of the stiffness shown in the larger elastogram.

UCL stiffnesses were quantified by placing four 1-mm circular ROIs consecutively along the length of the ligament, superficial to the head of the humerus (Figure 5A). The ROIs were placed in the distal 2/3 of the ligament to avoid ultrasound wave reflection off of the curved surface of the medial epicondyle and trough of the humerus, which we have observed distorting tissue stiffness measurements. Supraspinatus and infraspinatus muscle belly stiffnesses were quantified by placing a single circular region of interest of at least 9-mm diameter in the center of the muscle belly (Figure 5C, 5E). Efforts were made to avoid placing the region of interest at a depth which shearwave propagation was distorted by reflections off of the scapula. Supraspinatus and infraspinatus tendon stiffnesses were quantified by placing three 3-mm circular ROIs consecutively along the length of the tendon, superficial to the head of the humerus (Figure 5D, 5F). Biceps brachii long head muscle belly stiffnesses were quantified by placing a single circular region of interest of at least 8-mm diameter in the center of the muscle belly (Figure 5G). Biceps brachii long head tendon stiffnesses were quantified by placing four 2-mm circular ROIs consecutively along the length of the tendon, superficial to the head of the humerus, near the bicipital groove (Figure 5H).

In addition to measuring the material stiffness of the structures above, several structural properties of the UCL and medial elbow were also measured in this research. UCL length was measured from the ligament's origin on the medial epicondyle of the humerus to its insertion on the ulnar tubercle. UH joint space was measured as the linear distance from the most distal-medial aspect of the trochlea of the humerus to the most proximal-medial aspect of the ulna (Figure 5B). Delta of the UH joint space was calculated as the difference in UH joint space between the valgus-loaded and the supported condition.

Statistical Analysis

Mean values were calculated for each outcome measure from three separate trials during each imaging session. Intraclass correlation coefficients (ICC, 2,k) were calculated using the mean values to describe inter- and intra-rater measurement consistency. ICC values fell into one of five categories describing the reliability of the measurement: Slight (ICC <0.20), Poor (ICC = 0.21-0.40), Fair (ICC = 0.41-0.60), Good (ICC = 0.61-0.80), and Excellent (ICC = 0.81-1.00) . Standard errors of measurements (SEMs) were calculated to describe the precision of each of the measurements and are reported both as percentages of the mean and as raw values. Smaller SEMs signify greater precision with low measurement error magnitudes.

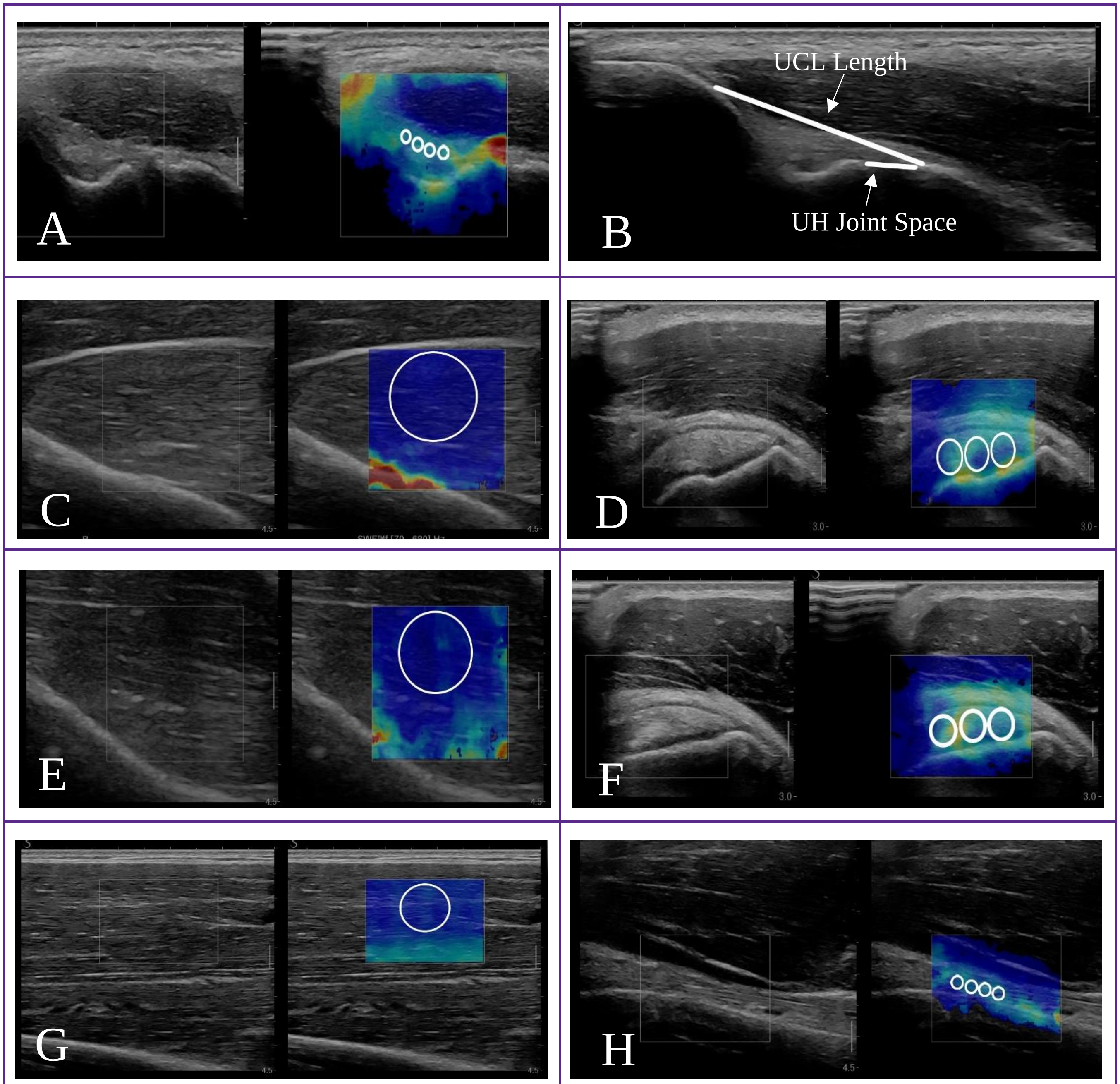


Figure 5. Representative image processing for each soft-tissue structure of interest.

a) UCL Stiffness
b) UCL Length and UH Joint Space
c) Supraspinatus Muscle
d) Supraspinatus Tendon
e) Infraspinatus Muscle
f) Infraspinatus Tendon
g) Biceps Brachii Long Head Muscle
h) Biceps Brachii Long Head Tendon

Results

16 recreationally active men between the ages of 18 and 30 voluntarily participated in this research. A sample of 20 generally healthy and recreationally active males was estimated to be sufficient to evaluate the reliability of the protocol based on prior musculoskeletal ultrasound imaging reliability studies using sample sizes between 15-25 participants (Bica et al., 2015; Rosskopf et al., 2016; Yamauchi et al., 2016). All participant demographics can be found in Table 1.

Table 1. Reliability Participant Demographics

	Mean	**SD**
n	16	
Height (m)	1.80	0.06
Mass (kg)	86.19	10.25
Age at Collection (yrs)	21.46	1.77
Throwing Arm (L/R)	1 / 15	

All tissues of interest were able to be sufficiently visualized in both B-mode and elastogram images in all participants. The use of shearwave elastography in this imaging protocol resulted in Good (ICC = 0.61 – 0.80) to Excellent (ICC = 0.81-1.00) intra- and inter-rater reliability for each of the soft-tissue structures of interest. Delta UH joint Space demonstrated Bad intra-rater reliability (ICC = 0.15) and Fair inter-rater reliability (ICC = 0.47). SEMs for intra-rater comparison ranged from 2.5-15.5% of the mean. SEMs for inter-rater comparison ranged from 2 – 19.5% of the mean. Mean and standard deviation values as well as ICC and SEMs for each tissue of interest are found in Table 2.

Table 2. Inter– and Intra-Rater Reliability Results

Inter-Rater Reliability

	Imager 1		Imager 2		ICC (2,k)	SEM	
	Mean	St. Dev	Mean	St. Dev		Raw Value	% of Mean
UCL Stiffness (kPa)	227.51	33.33	225.89	46.10	0.65	23.37	10.31
UCL Length (mm)	21.9	1.6	21.6	1.3	0.87	0.5	2.38
UH Joint Space - Supported (mm)	4.1	0.5	4.0	0.5	0.85	0.2	4.70
UH Joint Space - Valgus (mm)	4.5	0.6	4.4	0.5	0.80	0.2	5.23
Delta UH Joint Space (mm)	0.4	0.2	0.5	0.3	0.47	0.2	41.39
Supraspinatus Muscle (kPa)	22.03	5.55	22.33	6.14	0.85	2.21	9.95
Supraspinatus Tendon (kPa)	178.96	36.42	182.91	38.95	0.72	19.63	10.85
Infraspinatus Muscle (kPa)	23.56	8.38	26.36	7.23	0.62	4.80	19.25
Infraspinatus Tendon (kPa)	178.62	25.38	177.52	39.19	0.67	18.53	10.41
BBLH Muscle (kPa)	36.43	10.76	34.48	8.30	0.69	5.31	14.97
BBLH Tendon (kPa)	83.59	33.10	80.31	31.64	0.85	12.42	15.16

Intra-Rater Reliability

	Session 1		Session 2		ICC (2,k)	SEM	
	Mean	St. Dev	Mean	St. Dev		Raw Value	% of Mean
UCL Stiffness (kPa)	227.51	33.33	216.55	35.48	0.65	20.16	9.08
UCL Length (mm)	21.9	1.6	22.1	1.2	0.84	0.6	2.58
UH Joint Space - Supported (mm)	4.1	0.5	4.1	0.5	0.91	0.1	3.62
UH Joint Space - Valgus (mm)	4.5	0.6	4.2	1.2	0.69	0.5	11.98
Delta UH Joint Space (mm)	0.4	0.2	0.4	0.2	0.15	0.2	41.14
Supraspinatus Muscle (kPa)	22.03	5.55	23.79	6.27	0.81	2.57	11.24
Supraspinatus Tendon (kPa)	178.96	36.42	167.07	32.37	0.87	12.28	7.10
Infraspinatus Muscle (kPa)	23.56	8.38	23.82	7.11	0.77	3.66	15.43
Infraspinatus Tendon (kPa)	178.62	25.38	167.45	26.89	0.91	7.95	4.59
BBLH Muscle (kPa)	36.43	10.76	35.27	9.76	0.73	5.23	14.58
BBLH Tendon (kPa)	83.59	33.10	79.34	25.74	0.84	11.84	14.54

For all ICC(2,k) values, k indicates the mean value of three trials

Discussion

As the use of traditional and novel ultrasonic imaging techniques for the measurement of musculoskeletal tissue properties continues to increase it is critical that the reliability of the methods in which it is being used are tested and reported. The use of traditional and shearwave elastography ultrasound imaging continues to increase in athletic settings due to its price, real-time visualization, and relative portability (Bica et al., 2015; Lin et al., 2018; Takenaga et al., 2015). While recent studies have described the reliability of using shearwave ultrasound elastography to measure the structural and material properties of tissues of interest in the throwing arm, this is the first study to describe and measure the reliability of a single, comprehensive protocol for measuring structural and material properties of the most commonly injured soft-tissue structures in the throwing arms of overhead throwing athletes. Additionally, this is the first study to report the inter-rater reliability of shearwave elastography for the measurement of material stiffness several of the tissues examined in the protocol, including of the UCL.

The quantification of material stiffness in musculoskeletal applications has been reported in a variety of structures in recent years. Supraspinatus muscle has previous been found to be feasible in both cadaveric and in-vivo research (Baumer et al., 2017; Hatta et al., 2015; Itoigawa et al., 2015; Rosskopf et al., 2016). Rosskopf (2016) reported intra-observer ICC values of 0.70-0.80 and inter-observer ICC values of 0.89. Additionally, Baumer and colleagues (2017) reported good inter-rater and day-to day reliability for both the supraspinatus muscle and supraspinatus tendon. The use of SWE to quantify the stiffness of the infraspinatus has also been previously reported. Intra-rater reliability of ICC > 0.7 were reported in a study evaluating the effect of a stretching method on ROM and infraspinatus muscle stiffness in collegiate overhead athletes (Yamauchi et al., 2016). These results support our current findings of good inter- and intra-rater reliability of measuring supraspinatus, infraspinatus, and biceps brachii long head muscle and tendon stiffness using SWE.

The reliability of measuring UCL stiffness using shearwave ultrasound elastography has recently been described, although the two previous reports are not in agreement with each other. Lin (2017) examined a sample of healthy college aged individuals as well as a case-study of an injured pitcher, and report ICC values > 0.70 (Lin et al., 2018). On the other hand, a more recent paper reported ICC values of 0.05 for measuring UCL stiffness using SWE (Gupta et al., 2019). While this research did use a Telos machine to standardize arm position and apply a valgus load, we believe having the participant seated upright with their arm perpendicular to the ground, resting on the device or the table may contribute to the low ICC reliability values. The location of the UCL, and the need to hold the probe very gently and remain still to achieve accurate and repeatable shearwave measurements, may increase the difficulty of imaging the UCL with the participant seated and the arm perpendicular to the ground. When a participant lays supine and the arm is placed in a standardized position parallel to the ground, the UCL is now in a more superior location allowing for easier, and perhaps more reliable, elastography imaging. We believe the use of the adjustable-width arm position splint and having the participant laying supine with their arm abducted 60-80° at the shoulder contribute to our ICC values of approximately 0.65 for both intra- and inter-rater reliability.

Our results display a much lower ICC value for the reliability of measuring the UH joint space and delta UH joint space compared to prior reports. Previous literature has described this measurement as having Good to Excellent reliability in the throwing arms of baseball pitchers (Bica et al., 2015). This difference may be the magnitude of UH joint space and delta UH joint space. In overhead throwing athletes, larger UH joint spaces in throwing arm are common as well as larger deltas in the UH joint space with the application of a valgus load, compared to our sample of non-overhead throwing adult males. The smaller magnitude and variability of differences seen in UH gap space in our study approaches the limits of measurement precision on the ultrasound machine, possibly resulting in lower inter-and intra- rater reliability than has previously been seen in samples of baseball pitchers (Bica et al., 2015).

The difference between UH joint space measures and the measurement of the material stiffness of the UCL as it applies to understanding tissue properties in the medial elbow should also be discussed. Drastic changes in the delta UH joint space measurement have been related to the presence of a significant injury to the UCL, however the measurement UH joint space is truly a global measure of the laxity of the medial elbow. UCL stiffness measurements allow for the specific quantification of the ligament properties itself, as opposed to attempting to decipher the percent contributions of all of the soft tissues that cross the medial elbow. Thus, the ability to reliably measure the material properties of the UCL provide a new frontier into the information that is ably to be quickly, accurately, and non-invasively gathered about the health of an overhead throwing athlete's elbow.

The development of a comprehensive and reliable imaging protocol for visualizing and quantifying tissue properties in the throwing arms of overhead throwing athletes has several implications. Using SWE to further our understanding of the material properties of critical soft-tissue structures in the throwing arm may very well be the key to decreasing injuries in athletes that commonly suffer injuries related to the overhead throwing motion. Prior research has shown that muscles may display elevated material properties in areas of injury risk prior to the manifestation of injury symptoms (Salzano et al., 2015). In cross-sectional and short-term longitudinal studies, SWE has been previously used to identify chronic decreases and acute responses in the material properties of the UCL as a result of the load placed on the medial elbow during the overhead throwing motion. (Curran et al., 2016, 2019). In the shoulders of throwing athletes, SWE has been used to identify increased thickness and material stiffness in the posterior capsules of the throwing arm compared to the non-throwing arm (Takenaga et al., 2015). This change may be related to the eccentric loading experienced during the arm-deceleration phase of the overhead throwing motion as eccentric has been shown to increase muscle stiffness for as long as 21 days post-exercise (Lacourpaille et al., 2014; Xu et al., 2018). Having a single, comprehensive, and reliable imaging methodology to quantify the structural and material properties of soft-tissue structures in the throwing arm is essential for understanding the adaptations that occur from loading during throwing in both asymptomatic and injured overhead throwing athletes. Additionally, completion of the entire imaging protocol lasted between 15-20 minutes per arm, making the protocol reasonable to be implemented for semi-regular screening of athletes in a training room setting, with the goal of detecting deviations from an individual athlete's baseline measurements.

It should be acknowledged that the true relaxation state of individuals' elbow flexors was not ensured using muscle electromyography in this study. Participants were encouraged to remain as relaxed as possible, especially during imaging of the UCL and both imagers attempted to notice any guarding of the elbow joint through muscular contraction. Additionally, while this study does report Good to Excellent reliability for inter- and intra-rater reliability for all material stiffness outcome variables, one imager only performed imaging during one of the research sessions and intra-rater reliability for that imager was not calculated. This study design should have only minor implications on the reliability of the protocol as inter- and intra- rater reliability were similar for 10 out of the 11 tissue properties imaged in this research.

Conclusion

This research is the first to describe and validate a single comprehensive shearwave ultrasound elastography imaging protocol for the UCL, supraspinatus muscle and tendon, infraspinatus muscle and tendon and biceps brachii long head muscle and tendon. Reliable visualization and quantification of the material properties of these structures can play a crucial role in understanding the health of the throwing arms of overhead throwing athletes. Athletes such as baseball pitchers, cricket bowlers, and javelin throwers all frequently suffer injuries to these structures resulting from the repetitive high loading of the tissues during the throwing motion. Future research should examine adaptations in these structures in overhead throwing athletes to better understand the effect of the throwing motion on the material properties of the tissues, as well as to examine any relationships between tissue properties and injury risk factors.

CHAPTER 3: RELATIONSHIPS BETWEEN KINETIC INJURY RISK FACTORS AND THE MATERIAL STIFFNESS OF CRITICAL SOFT-TISSUE STRUCTURES IN THE THROWING ARMS OF BASEBALL PITCHERS.

Introduction

The overhead throwing motion used in baseball pitching is an extremely complex and dynamic motion involving most of the kinetic chain, and ultimately results in extreme loads being placed on the shoulder and elbow of the throwing arm. In 1995, Dr. Fleisig and his colleagues published a thorough examination of the kinetics and kinematics of "highly skilled" adult baseball pitchers and related their findings to known mechanisms of overuse injuries common in baseball pitchers. Their findings highlighted the two critical points in the throwing motion, the late arm-cocking and arm deceleration phases, during which soft-tissue structures in the shoulder and elbow are highly stressed and most likely to suffer from overuse injuries during this time (Fleisig et al., 1995).

Near the end of the arm-cocking phase, the structures of the elbow must resist a tremendous external valgus load and the structures of the shoulder also produce a large internal rotation torque and a large anterior force (Fleisig et al., 1995). Cadaveric research has reported that the UCL can be responsible for resisting approximately 50% of valgus loading on the elbow, and has a failure load of approximately 32 Nm of valgus torque (Morrey and an, 1983). The magnitude of the varus torque generated in the medial elbow during the arm-cocking phase has been reported between 60 – 120 Nm, and the contribution of the UCL to resisting that varus torque places the UCL near its maximum resistive capacity during this phase of the pitching motion (Aguinaldo and Chambers, 2009; Anz et al., 2010; Fleisig et al., 1995; Werner et al., 1993). While 50% of more than 64 Nm of valgus torque should place the UCL above its failure point, the role of active contractions of soft-tissues crossing the elbow during the pitching motion as opposed to in cadaveric work can not be overlooked (Buffi et al., 2015; Fortenbaugh et al., 2009). During the arm deceleration phase of the pitching motion, the structures of the shoulder must resist an extremely large distractive force generated by the arm's forward momentum. The musculature of the posterior shoulder, including the supraspinatus and infraspinatus, are susceptible to tensile failure and injury at this point in the motion as they must act to resist glenohumeral distraction and internal rotation, and horizontal shoulder adduction (Andrews and Angelo, 1988; Fleisig et al., 1995). During this deceleration phase, supraspinatus or biceps tendinitis may also develop due to the position of the arm and need for a large compressive force at the shoulder. Pitchers with anterior instability may produce even larger loads with the biceps tendon-labrum complex (Andrews and Angelo, 1988; Fleisig et al., 1995; Glousman et al., 1988).

Most baseball researchers agree that the majority of injuries in baseball pitchers are a product of accumulated microtrauma resulting from the large forces and torques exerted at the shoulder and elbow during the overhead throwing motion (Andrews et al., 1985; Andrews and Angelo, 1988; Buffi et al., 2015; Fleisig et al., 1995; Wilk et al., 2004). The repetitive loading of soft-tissue structures, while sub-maximal, has the potential to lead to chronic breakdown in tissue and eventual injury. Cyclic loading has shown the potential to cause fatigue failure at high, but sub-maximal, loads in collagenous structures such as tendon and ligaments (Thornton et al., 2007; Wojtys et al., 2016). In ligaments, repetitive sub-maximal loading which leads to scarring can alter the creep properties of the tissues and it is known that the combination of a high loading magnitude and shortened rest intervals can increase the maximum consequences of muscle microtrauma (Gao Smith and Gallagher, 2015; Thornton et al., 2000). While the high magnitude of loading is described as a concern, it is the repetitive exposure to such high loads that makes two specific parts of the baseball pitching motion specific timepoints of concern. It is in these times, the arm-cocking and arm deceleration phases, during which the soft-tissue structures of the shoulder and elbow of the throwing arm are under the highest loads and believed to be at the greatest risk of injury (Fleisig et al., 1995; Park et al., 2002a).

Recent research has confirmed those initial suggestions, demonstrating that elevated elbow valgus and shoulder external rotation torques during the late arm-cocking phase of the motion are related to higher incidence of elbow injury in baseball pitchers (Anz et al., 2010). Most recent pitching research agrees elevated elbow valgus torque, increased shoulder maximum external rotation torque and elevated shoulder distraction force are likely the kinetic factors behind overuse injuries (Aguinaldo and Chambers, 2009; Fleisig et al., 1995; Fortenbaugh et al., 2009; Werner et al., 2007, 1999). However, in the 25 years since Fleisig and colleagues (1995) first identified these critical phases and mechanical factors, the chronic effect of a pitcher's throwing mechanics has on the material properties of critical soft-tissue structures in the throwing arm remains unknown. While several kinetic and kinematic variables have been suggested to be overuse injury risk factors in baseball pitching (Escamilla et al., 2007; Fleisig, 2015; Fleisig et al., 1995; Werner et al., 2007), the links between individual kinetic and kinematic aspects of the pitching motion and changes in the properties of the most commonly injured soft-tissue structures in baseball pitchers has not been previously investigated.

While submaximal, this level of repetitive loading is believed to cause microtrauma resulting not only in overuse injuries in baseball pitchers, but also the cause of structural and material property adaptations in asymptomatic baseball pitchers(Sasaki et al., 2002). Structural changes have been reported in the shoulders and elbows of pitchers for more than 20 years. Data from our lab has been consistent with the findings of many other research groups demonstrating increased length and thickness of the UCL, and increased ulnohumeral gap in the throwing arms of baseball pitchers compared to their non-throwing arms (Atanda et al., 2015; Bica et al., 2015; Ciccotti et al., 2014; Curran et al., 2016; Keller et al., 2015; Marshall et al., 2015; Nazarian et al., 2003). Despite these consistent bilateral differences and the high incidence of shoulder and elbow injury in baseball pitchers, only a dramatic widening of the ulnohumeral gap with the application of a valgus load has been described as an indicator of existing UCL injury, but not an indicator of elevated risk prior to injury occurrence (Ciccotti et al., 2014). The failure of any of the structural changes to critical soft-tissue structures to be a strong predictor of future injury indicates the need to expand research into new directions to determine indicators of elevated injury risk.

Preliminary data from our lab at ECU has shown the potential for using shearwave ultrasound elastography to identify changes in material properties, such as tissue stiffness, which may be indicators of elevated injury risk (Salzano et al., 2015). In asymptomatic baseball pitchers, we have previously identified bilateral differences in the material stiffness of the UCL, showing significantly lower material stiffness in the throwing arm than the non-throwing arm in during a pre-season research session (Curran et al., 2016). This difference suggests the presence of damage or tensile failiure experienced by the ligament during repetitive pitching, resulting in increased medial joint laxity and the structural observation of increases in ulnohumeral joint gap. This decreased stiffness believed to be resulting from microtrauma was corroborated in a recent case report on an injured baseball pitcher (Lin et al., 2018). Additionally, the infraspinatus and teres minor of the throwing shoulder have demonstrated increased muscle stiffness compared to the non-throwing shoulder in baseball pitchers (Yamauchi et al., 2016). This result is consistent with findings from Lacourpaille and colleagues that muscle stiffness was elevated after eccentric exercise, and that the increased stiffness could still be present 21 days later if eccentric loading occurs at longer muscle lengths (Lacourpaille et al., 2014). Preliminary evidence also suggests musculotendinous stiffness of the posterior rotator cuff as the primary mechanism for shoulder ROM deficits in baseball players (Bailey et al., 2015), again describing material property changes as the probable initial cause for the structural adaptations often reported in baseball pitchers. These prior studies support our belief that further understanding of the changes in the material stiffness of the critical soft-tissue structures in the throwing arm is the key to decreasing injuries in baseball pitchers.

While these results do show that the stress of the overhead throwing motion does have a chronic effect, it is unknown if the magnitude of the bilateral differences observed in tissue properties are correlated with kinetic and kinematic variables in the baseball pitching motion. **Therefore, the purpose of this research was to examine relationships between baseball pitching mechanics and the properties of critical soft-tissue structures in the throwing arms of baseball pitchers.** If the chronic valgus loading of the UCL causes chronic microtrauma within the ligament, we anticipate that pitchers with mechanics causing greater peak elbow valgus torques will display decreased material stiffness of the UCL. Likewise, knowing that the supraspinatus, infraspinatus, and biceps long head are all loaded eccentrically at high rates of speed and at extended lengths during the arm deceleration phase, we also expect to find increased material stiffness in the muscles and tendons of the throwing shoulder in pitchers whose throwing motion generates greater distractive forces at the shoulder joint. Establishing the relationships between kinetic and kinematic risk factors and tissue properties may shed new light on the specific mechanisms of overuse injuries to pitchers, allowing for better preventative treatment and care.

This information may also provide additional outcome measures for future prospective research studies rather than relying on the onset of significant injuries.

Methods

To examine relationships between throwing mechanics and the material properties of soft-tissue structures in the throwing arm of baseball pitchers, bilateral shearwave ultrasound elastography imaging and 3D motion capture of the pitching motion were performed on 26 currently competitive adult baseball pitchers. Participant demographics can be found in Table 3. All pitchers were between the ages of 18-40 and were either currently listed on a competitive baseball roster or were free-agents training to compete in the upcoming season. Additional exclusion criteria for this study included any surgery on their throwing arm in the previous 12 months, or a history of UCL repair or replacement. Pitchers participated in two separate research sessions on separate days; the 3D motion capture of the pitching motion was performed during one session and the ultrasound elastography images were collected during the other session. Upon arriving for their first research session, participants provided informed consent, had their height and weight measured, and completed a questionnaire including regarding their demographics, baseball playing and injury history, and recent exercise and throwing loads. Participants also completed the Kerlan-Jobe Orthopaedic Clinic (KJOC) Shoulder and Elbow questionnaire. Participants were instructed not to pitch and to avoid heavy upper-extremity resistance training in the 48 hours prior to either session.

Table 3. Baseball Pitcher Participant Demographics

n	26
Height (m)	1.84 ± 0.06
Mass (kg)	86.19 ± 12.36
Age at Collection (yrs)	20.22 ± 1.50
Throwing Arm (L/R)	6 / 20

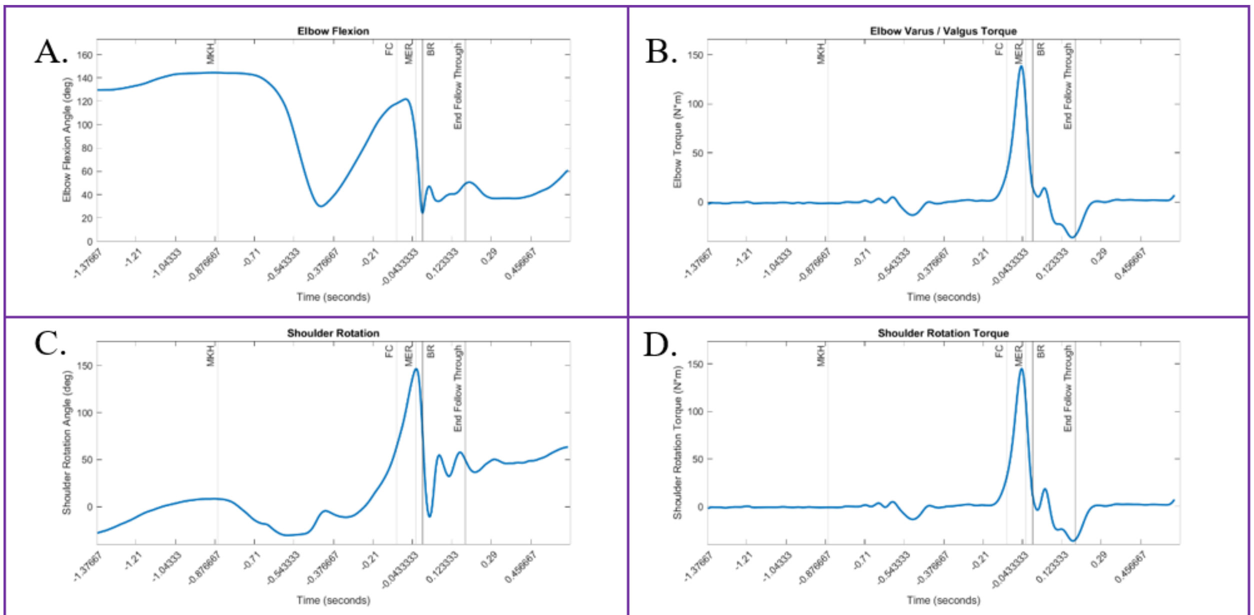
Material stiffness measurements of the supraspinatus muscle and tendon, infraspinatus muscle and tendon, biceps brachii long head muscle (BBLH) and tendon, and UCL were collected from ultrasound elastography images. All imaging was performed using an Aixplorer (Supersonic Imagine, Aix-en-Provence, France) Ultrasound system. Images of each soft-tissue structure of interest were collected in a split screen mode, displaying B-mode (traditional ultrasound) to allow for clear identification of structural parameters of the tissues, and an elastogram (shearwave elastography colormap overlay) for the measurement of the tissue stiffness. Measurements for each outcome measure were taken from three separate images, all displaying sufficient shearwave propagation throughout the entire tissue of interest. All images were taken by a single member of the research team (CC) who has demonstrated Good (ICC = 0.61-0.80) to Excellent (ICC = 0.81 – 1.00) intra-rater reliability for measuring material stiffness of each of the soft-tissue structures of interest in the current study (see Chapter 1).

12 Qualisys Oqus cameras (Qualisys AB, Göteborg, Sweden) were used to collect passive-marker motion data at 300 Hz for each participant. A full-body, 52 reflective marker set was used to identify skeletal landmarks bilaterally on the body of each pitcher, based off of a previously described marker set (Boddy et al., 2019). The specific marker set and processing details can be found in Appendix D. After the markers were placed, participants were given as much time as necessary to stretch and warm up prior to pitching. Pitchers then threw 10 consecutive fastball pitches at full effort. All motion data was processed in Visual 3D (C-Motion Inc., Germantown, MD, USA). A full body skeletal model was constructed from the skeletal landmark and tracking markers used. The baseball was modeled as a .142 kg point mass, interacting with the throwing hand at the midpoint between the 2nd and 5th metacarpal markers until the point of ball release. The

ball was excluded from analysis after ball release. Full body kinetic and kinematic variables were calculated using ISB recommendations for joint coordinate systems (Wu et al., 2005)

Seven kinetic variables of interest were calculated for each of the fastballs analyzed and means and standard deviations of each were recorded for each pitcher. Maximum shoulder compressive force was calculated as the maximum force along the long axis of the upper throwing arm created by the shoulder capsule and soft-tissue structures to resist shoulder distraction during the pitching motion. Mean shoulder compressive force was calculated as the average force along the long axis of the upper throwing arm between foot contact and ball release. Mean shoulder compressive force post release was calculated as the average force along the long axis of the upper throwing arm between ball release and the end of the follow through. Maximum shoulder external rotation torque was calculated as the maximum upper arm torque about the long axis of the upper throwing arm during the pitching motion. Mean shoulder external rotation torque was calculated as the average upper arm torque about the along the long axis of the upper throwing arm between foot contact and ball release. Maximum elbow external valgus torque was calculated as the maximum forearm torque along the long axis of the upper throwing arm during the pitching motion. Mean elbow external valgus torque was calculated as the average torque along the long axis of the upper throwing arm between foot contact and ball release. Representative plots displaying elbow flexion, elbow torque, shoulder internal and external rotation, shoulder external rotation torque, and shoulder compressive force for one participant can be seen in Figure 6. These figures are similar both in value and in shape/timing to those in previously published literature (Fleisig et al., 1995; Kaizu et al., 2018; Werner et al., 1993). For a more complete explanation of processing details, see Appendix D.

Bilateral differences in tissue properties were analyzed using dependent sample t-tests. Correlational analyses will be performed in MATLAB (Mathworks Inc., Natick, MA) to analyze relationships between the properties of each of the soft tissues of interest in the throwing arm and the kinetic variables of interest of the pitching motion. Additional correlational analyses will be used to analyze relationships between the magnitudes of bilateral differences in the properties of the tissues and the kinetic variables of interest of the pitching motion. In all analyses, statistical significance was determined at $p < 0.05$ and statistical trends were determined at $0.05 < p < 0.10$ (Curran-Everett and Benos, 2004).



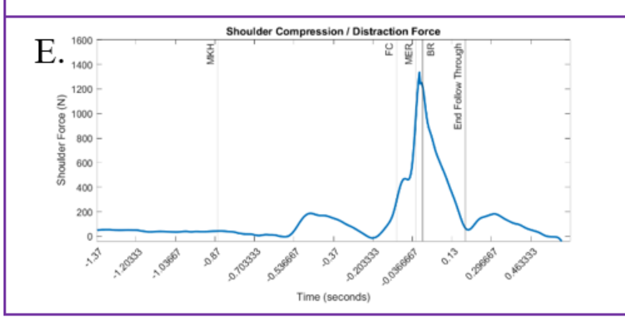


Figure 6.
Representative plots displaying A) elbow flexion, B) elbow torque, C) shoulder internal and external rotation, D) shoulder external rotation torque, and E) shoulder compressive force for one participant. Key timepoints shown include maximum knee height (MKH), front foot contact (FC), maximum shoulder external rotation (MER), and ball release (BR).

Results

Results for the key kinetic and kinematic variables are shown in Table 4. Bilateral results for the structural and material properties of each of the soft-tissue structures of interest are shown in Table 5. Several soft-tissue properties showed significant differences between the throwing arms of baseball pitchers and the non-throwing arms. The UCL of the throwing arm displayed longer lengths (22.1 ± 1.5 mm vs 21.3 ± 1.4 mm, $p = 0.0008$) and lower material stiffness (197.7 ± 20.2 kPa vs 234.4 ± 33.2 kPa, $p < 0.00001$) under valgus load than the UCL in the non-throwing arm (Figure 7). Additionally, the measurements taken of the ulnohumeral (UH) joint space, which is commonly used as a descriptor of the UCL were all greater in the throwing arm including UH joint space in a supported condition (4.2 ± 0.6 mm vs 3.7 ± 0.5 mm, $p < 0.00001$), UH joint space in a valgus loaded condition (5.0 ± 0.7 mm vs 4.2 ± 0.5 mm, $p < 0.00001$), and the delta UH joint space between conditions (0.8 ± 0.4 mm vs 0.5 ± 0.2 mm, $p = .0008$) (Figure 8). The infraspinatus tendon had significantly greater material stiffness in the throwing arm than the non-throwing arm (200.5 ± 34.4 kPa vs 174.5 ± 34.0 kPa, $p = 0.0006$), and the supraspinatus muscle trended towards being significantly stiffer in the throwing arm than in the non-throwing arm (27.9 ± 9.0 kPa vs 25.0 ± 8.2 kPa, $p = 0.097$) (Figure 9). No significant differences were observed for the material stiffness of the supraspinatus muscle or tendon, infraspinatus muscle, or biceps brachii long head muscle or tendon.

Table 4. Throwing Mechanics Outcome Variables	
	Mean ± SD
Max Shoulder Compressive Force (N)	1009.27 ± 245.16
Mean Shoulder Compressive Force (N)	457.15 ± 114.80
Mean Shoulder Compressive Force Post Release (N)	424.14 ± 119.34
Max Shoulder External Rotational Torque (Nm)	90.28 ± 20.67
Mean Shoulder External Rotation Torque (Nm)	55.18 ± 12.57
Max Elbow External Valgus Torque (Nm)	85.12 ± 19.65
Mean Elbow External Valgus Torque (Nm)	51.98 ± 11.98

Table 5. Bilateral Critical Soft-Tissue Properties **$p < 0.05$;** *$0.05 < p < 0.01$*			
	Throwing Arm Mean ± SD	**Non-Throwing Arm Mean ± SD**	**p-Value**
UCL Stiffness (kPa)	**197.7 ± 20.2**	**234.4 ± 33.2**	**< 0.00001**
UCL Length (mm)	**22.1 ± 1.5**	**21.3 ± 1.4**	**0.0008**
UH Joint Space – Supported (mm)	**4.2 ± 0.6**	**3.7 ± 0.5**	**< 0.00001**
UH Joint Space – Stressed (mm)	**5.0 ± 0.7**	**4.2 ± 0.5**	**< 0.00001**
UH Joint Space – Delta (mm)	**0.8 ± 0.4**	**0.5 ± 0.2**	**0.004**
Supraspinatus Muscle Stiffness (kPa)	*27.9 ± 9.0*	*25.0 ± 8.2*	*0.097*
Supraspinatus Tendon Stiffness (kPa)	184.6 ± 36.0	173.6 ± 30.0	0.145
Infraspinatus Muscle Stiffness (kPa)	24.3 ± 5.2	22.1 ± 8.5	0.198
Infraspinatus Tendon Stiffness (kPa)	**200.5 ± 34.4**	**174.5 ± 34.0**	**0.0006**
BBLH Muscle Stiffness (kPa)	37.5 ± 8.6	36.6 ± 7.7	0.553
BBLH Tendon Stiffness (kPa)	78.0 ± 25.2	82.5 ± 22.4	0.285

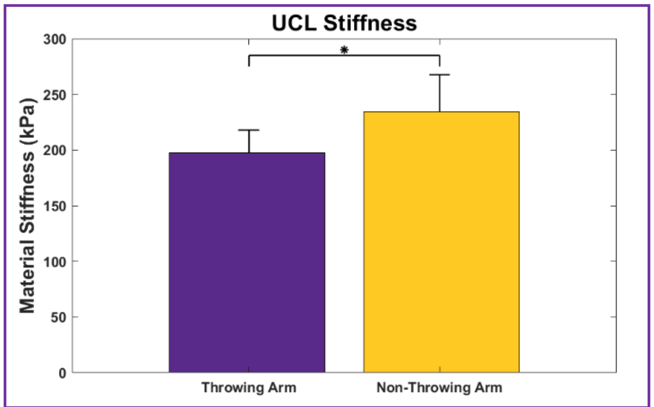


Figure 7. Bilateral difference in material stiffness of the UCL. *p < 0.05

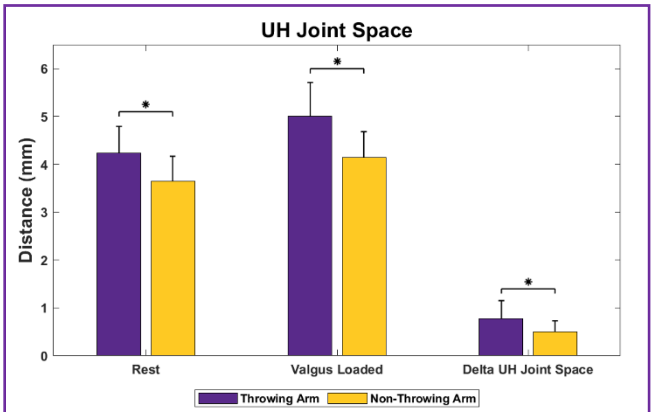


Figure 8. Bilateral differences in ulnohumeral joint space measures. *p < 0.05

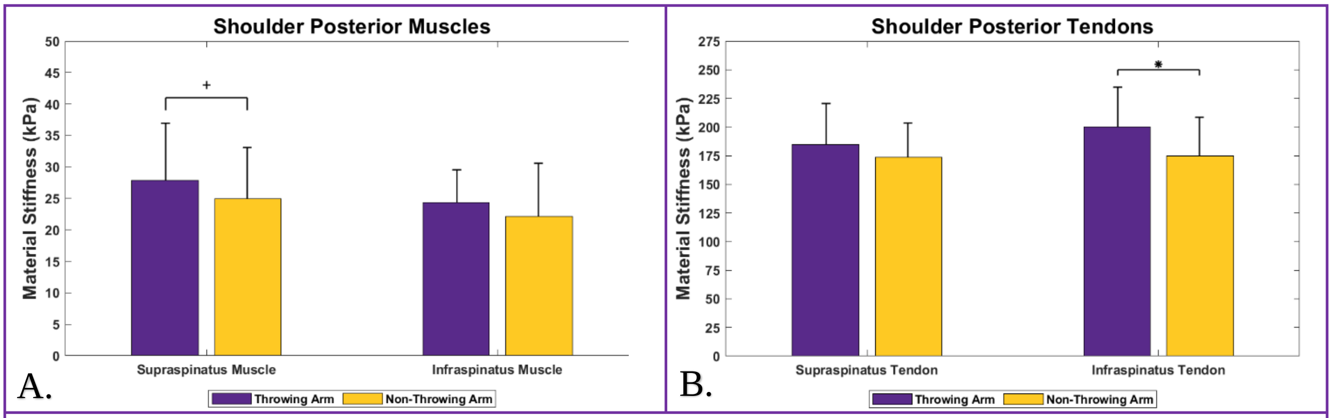


Figure 9. Bilateral differences in material stiffness of supraspinatus and infraspinatus muscles (A) and tendons (B). * p< 0.05 $^{+}$ 0.05 < p < 0.10

Pearson's correlation values for relationships between pitching mechanics and tissue properties are shown in Table 6. Correlation plots for all relationships between supraspinatus and infraspinatus material properties and peak and mean shoulder compression force can be found in Figures 10 and 11. Correlations plots for relationships between UCL stiffness and peak and mean elbow valgus torque can be found in Figure 12. Additional significant correlations can be found in Figure 13. Significant relationships were found demonstrating that pitchers who threw with elevated shoulder kinetics had lower material stiffness in the tendons of the rotator cuff in the throwing arm. There was a significant relationship between elevated mean shoulder compressive force and decreased supraspinatus tendon stiffness ($r = -0.411$, $p = 0.0370$), decreased infraspinatus tendon stiffness ($r = -0.430$, $p = 0.029$), and decreased biceps brachii long head tendon stiffness ($r = -0.477$, $p = 0.014$). Additionally, elevated mean shoulder compressive force post ball release was significantly correlated with decreased infraspinatus tendon stiffness ($r = -0.407$, $p = 0.039$) and decreased biceps brachii muscle stiffness ($r = -0.501$, $p = 0.009$). Finally, elevated max shoulder external rotation torque was significantly correlated with decreased biceps brachii long head tendon stiffness ($r = -0.413$, $p = 0.036$). There were no significant correlations between bilateral differences in tissue properties and any of the pitching mechanics outcome variables examined.

Table 6. Correlations between Tissue Properties and Throwing Mechanics.
***p <0.05; ⁑ 0.05 < p < 0.1**

		Max Shoulder Compressive Force	Mean Shoulder Compressive Force	Mean Shoulder Compressive Force Post Release	Max Shoulder External Rotational Torque	Mean Shoulder External Rotation Torque	Max Elbow Valgus Torque	Mean Elbow Valgus Torque
THROWING ARM	Supraspinatus Muscle	0.211	0.280	0.191	0.144	0.191	0.139	0.190
	Supraspinatus Tendon	**-0.385⁑**	**-0.411***	**-0.347⁑**	**-0.365⁑**	-0.270	**-0.336⁑**	-0.252
	Infraspinatus Muscle	0.279	0.228	0.121	0.146	0.164	0.166	0.177
	Infraspinatus Tendon	**-0.366⁑**	**-0.429***	**-0.407***	**-0.355⁑**	-0.243	-0.329	-0.230
	BBLH Muscle	-0.285	**-0.383⁑**	**-0.501***	0.013	0.144	0.041	0.157
	BBLH Tendon	**-0.372⁑**	**-0.477***	**-0.378⁑**	**-0.413***	**-0.354⁑**	**-0.388⁑**	**-0.335⁑**
	UH Joint Space - Supported	-0.108	-0.064	-0.128	0.111	0.100	0.119	0.096
	UH Joint Space - Stressed	-0.016	-0.002	-0.116	0.033	0.098	0.031	0.088
	UH Joint Space - Delta	0.129	0.089	-0.026	-0.102	0.034	-0.117	0.021
	UCL Length	-0.169	-0.038	-0.149	-0.222	-0.070	-0.219	-0.063
	UCL Stiffness	-0.229	-0.255	-0.176	0.024	-0.021	0.048	-0.016
BILATERAL DIFFERENCE	Supraspinatus Muscle	-0.060	-0.138	-0.208	-0.120	-0.221	-0.130	-0.060
	Supraspinatus Tendon	0.023	0.056	-0.154	-0.042	-0.122	-0.026	0.023
	Infraspinatus Muscle	-0.239	-0.237	-0.010	-0.026	-0.012	-0.026	-0.239
	Infraspinatus Tendon	-0.078	-0.174	-0.129	-0.100	-0.117	-0.094	-0.078
	BBLH Muscle	-0.202	-0.306	-0.125	0.007	-0.122	0.010	-0.202
	BBLH Tendon	-0.292	-0.192	-0.233	-0.223	-0.234	-0.216	-0.292
	UH Joint Space - Supported	0.005	-0.006	0.263	0.268	0.299	0.279	0.005
	UH Joint Space - Stressed	0.016	-0.074	0.192	0.299	0.208	0.294	0.016
	UH Joint Space - Delta	0.015	-0.088	-0.077	0.056	-0.101	0.036	0.015
	UCL Length	0.117	0.010	0.059	0.109	0.080	0.122	0.117
	UCL Stiffness	-0.160	-0.076	-0.212	-0.271	-0.219	-0.276	-0.160

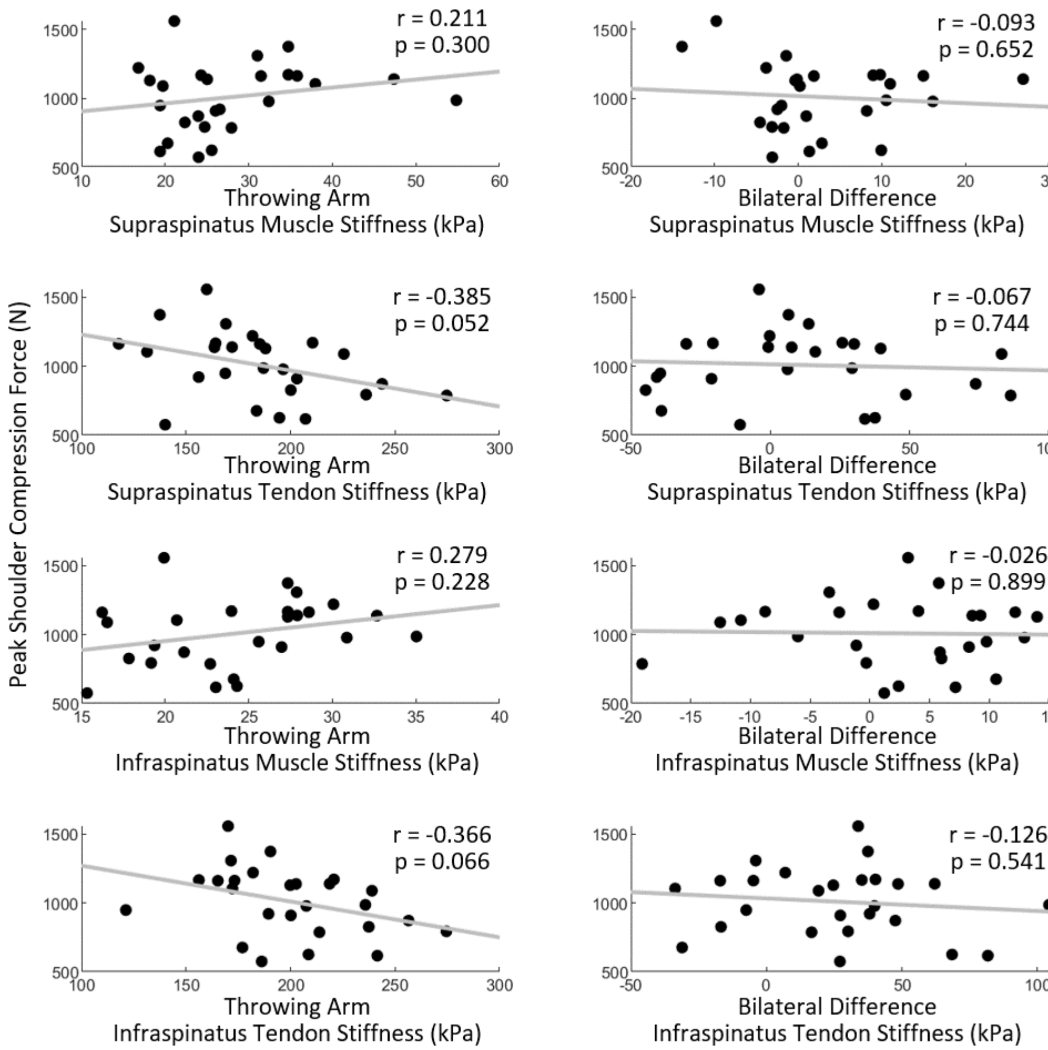


Figure 10. Correlations between supraspinatus and infraspinatus material stiffness and peak shoulder compression force.

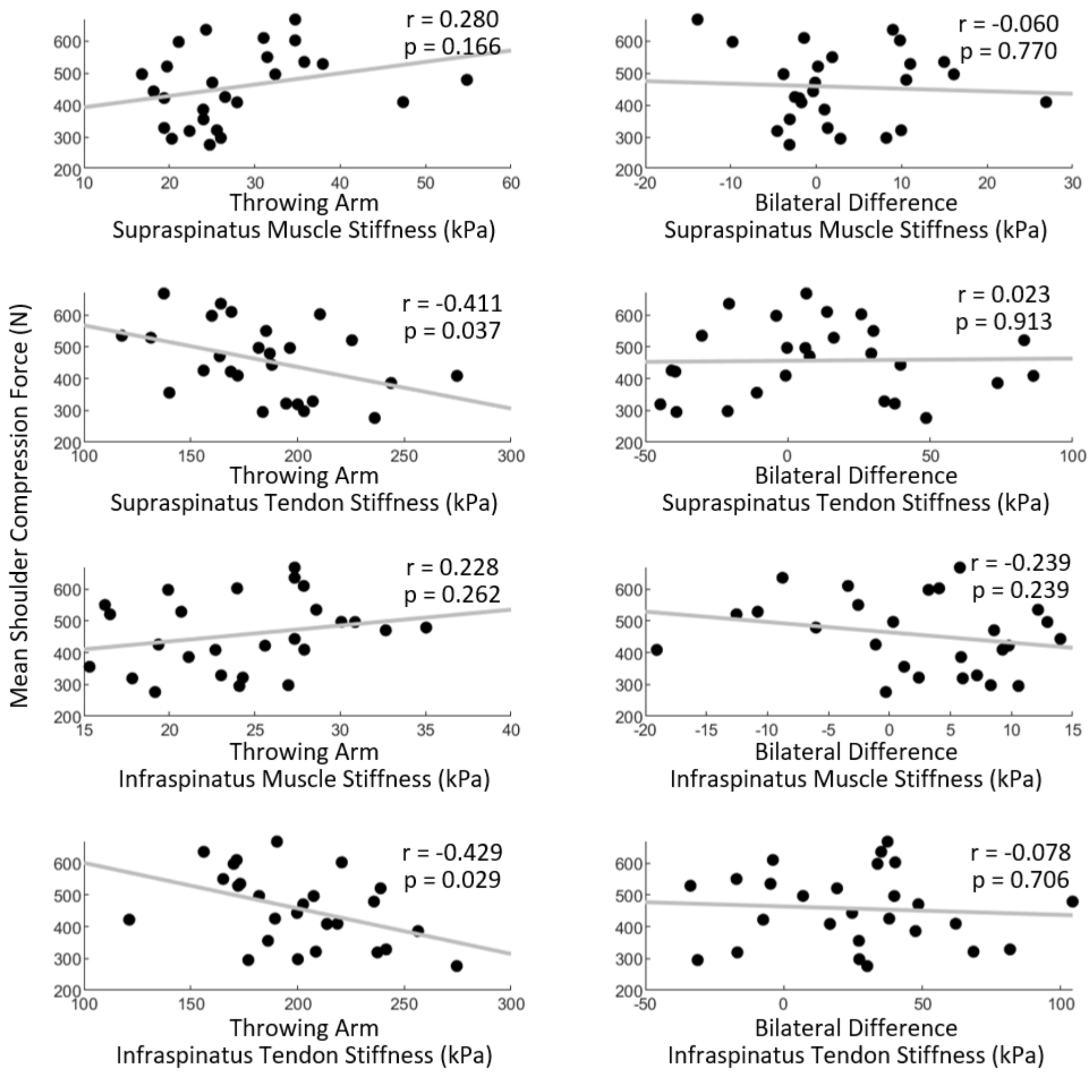


Figure 11. Correlations between supraspinatus and infraspinatus material stiffness and mean shoulder compression force.

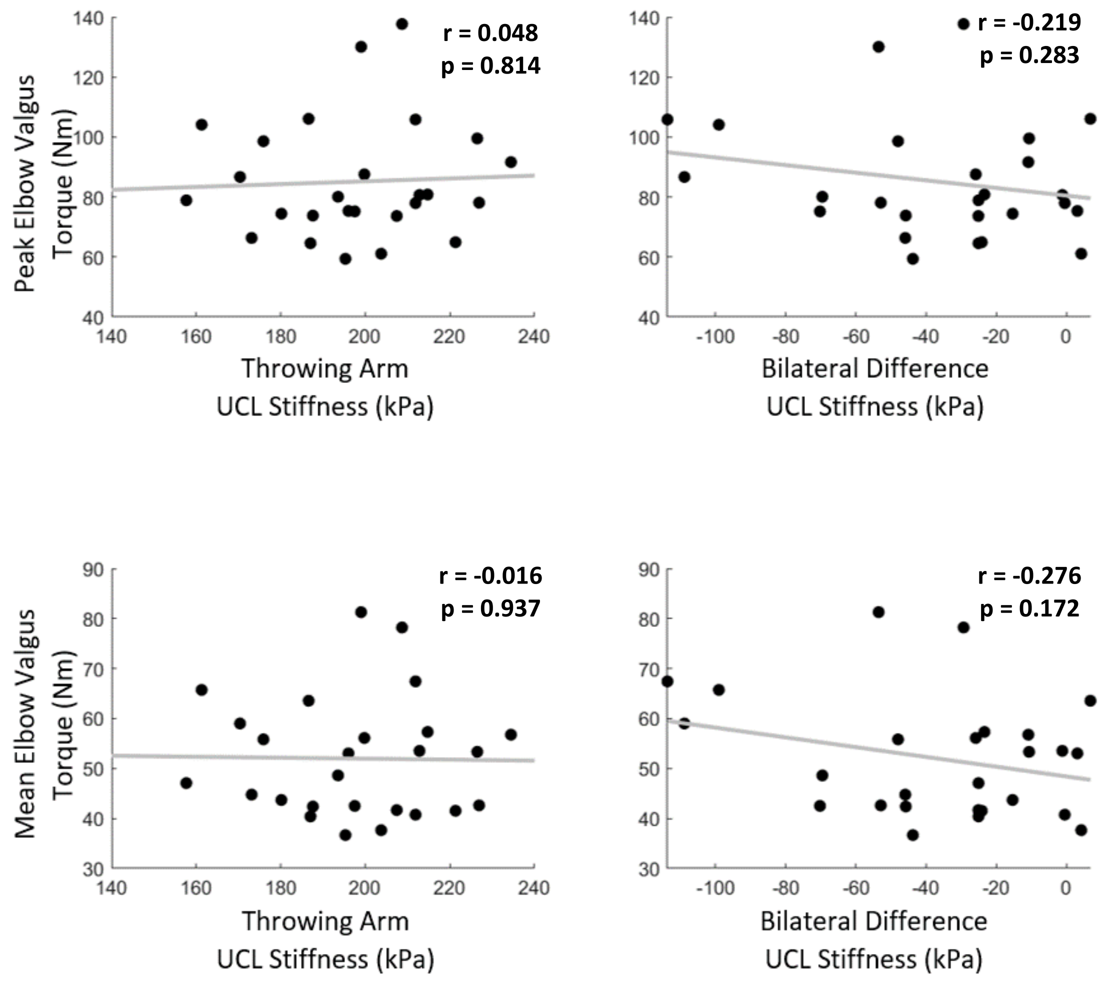


Figure 12. Correlations between UCL material stiffness and elbow valgus torque.

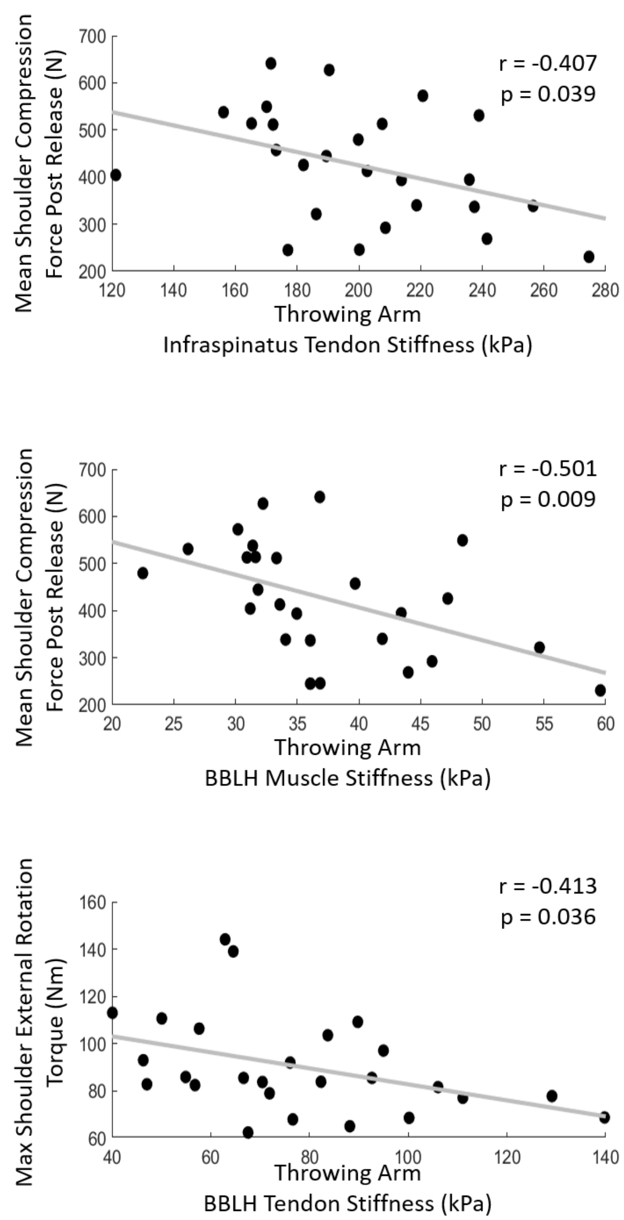


Figure 13. Other significant correlations between tissue material stiffness in the throwing arm and pitching kinetics.

Discussion

This research is the first to identify relationships between the structural and material properties of soft-tissue structures of the throwing arm and the kinetics of the throwing motion. This information provides a new insight into the specific mechanisms of the differences seen in the soft tissues of the throwing arms of baseball pitchers. The results demonstrate relationships shoulder kinetics during the pitching motion and the material properties of the supraspinatus and infraspinatus tendons, however the relationship was inverse to the hypothesized relationship. Additionally, the results did not confirm the hypothesis that elevated elbow kinetics would be related to decreased material stiffness of the UCL.

The bilateral comparison of structural and material properties of critical soft-tissue structures in the arms of baseball pitchers continues to demonstrate the unilateral effects of the overhead throwing motion used in baseball pitching on the structures of the throwing arm. As reported in Appendix D, UCL length was the only property measured which differed bilaterally. (significantly longer in the throwing arm), in a sample of 16 healthy adult males, who were not competitive overhead throwing athletes. Other research has also reported no bilateral differences in the material properties of critical throwing arm structures such as the UCL in non-pitcher adults (Gupta et al., 2019). This suggests that any bilateral differences in structural or material properties in healthy adult male baseball pitchers other than UCL length may be due to the extremely high loads experienced by the throwing arm during the overhead throwing motion.

Our results show increased medial elbow laxity and decreased material stiffness of the UCL in the throwing arm compared to the non-throwing arm. This result is in concert with previous findings from our lab demonstrating decreased UCL material stiffness in the throwing arms of baseball pitchers during a pre-season imaging session, suggesting a chronic adaptation to the valgus loading experienced during the pitching motion. (Curran et al., 2016). Our findings also align with a recent finding demonstrating much greater bilateral differences in a case report of a pitcher with a UCL injury (Lin et al., 2018). This increased medial elbow laxity is supported by our results of increased UH joint space under valgus load and the delta UH joint space from rest to valgus-loaded in the throwing arm compared to the non-throwing arm, a finding commonly reported in imaging studies of the medial elbow in baseball pitchers (Atanda et al., 2015; Bica et al., 2015; Ciccotti et al., 2014; Curran et al., 2016; Nazarian et al., 2003; Sasaki et al., 2002).

In the soft-tissue structures of the posterior shoulder, our results showed increased material stiffness overall compared to the non-throwing arm. Specifically, the infraspinatus tendon was significantly stiffer, and the supraspinatus muscle trended towards having increased material stiffness in the throwing shoulders of baseball pitchers. Our results align well with prior research reporting significant increases in the material stiffness of the supraspinatus, infraspinatus and teres minor of the throwing shoulder in baseball pitchers (Kobayashi et al., 2019; Yamauchi et al., 2016). Each time a pitcher throws, the posterior shoulder muscles and tendons are tasked with contracting eccentrically in order to decelerate the anterior translation of the shoulder and maintain proper alignment of the shoulder girdle. Additionally, the supraspinatus and infraspinatus act to decrease internal rotation of the humerus. Lacourpaille and colleagues have reported muscle stiffness elevation after eccentric exercise, and that the increased stiffness could still be present 21 days later if eccentric loading occurs at longer muscle lengths (Lacourpaille et al., 2014). There is some belief that this chronic increase in material stiffness may be a healthy adaptation as a decrease in material stiffness of the supraspinatus in the throwing shoulder may indicate elevated risk of future pain in the throwing shoulder (Kobayashi et al., 2019).

The kinetic results from the 3D motion analysis of pitchers in this study also continues to demonstrate the extreme stresses placed on the throwing arm during the critical phases of the baseball pitching motion. Maximum and mean shoulder compressive force, shoulder and external rotation torque, and elbow valgus torque all demonstrate the loads placed on the shoulder and elbow during the late arm-cocking and arm acceleration phases. Mean shoulder compressive force post release shows the load placed on the shoulder during the arm deceleration phases.

This research looked at both peak kinetic values as well as means within specific ranges of time, whereas most of the prior literature has focused on the peak values or values at specific kinematic events. This present research looked at both peaks and total stresses in order to gain a better understanding of the average loading that might affect the soft-tissue structures of interest. The results of this research report a peak elbow external valgus torque of 85.12 ± 19.65 Nm, occurring just prior to maximum external rotation of the throwing shoulder. This value falls within the range of 64 – 120 Nm, values commonly reported for the measurement in prior publications (Aguinaldo and Chambers, 2009; Anz et al., 2010; Fleisig et al., 1995; Werner et al., 1999, 1993). The peak shoulder compressive force in the current study was 1009.27 ± 245.16 N, in line with that reported in previous literature (Fleisig et al., 1995). Finally, the peak shoulder external rotation torque of 90.28, occurring near the instant of maximum shoulder external rotation, was also similar to the values of previous literature ranging from 67 – 100 Nm (Anz et al., 2010; Fleisig et al., 1995).

This research does not demonstrate any significant relationships between elbow external valgus torque during the baseball pitching motion and the material stiffness of the UCL in the throwing arm. This runs counter to our hypothesis that "*pitchers with mechanics causing greater peak elbow valgus torques will display decreased material stiffness of the UCL.*" In fact, none of the seven kinetic factors of the pitching motion were correlated with either the material stiffness of the UCL in the throwing arm or the magnitude of the bilateral difference in the material stiffness of the UCL. The lack of relationship demonstrated here is truly an unexpected finding and runs counter to the suggestions of the majority of baseball injury literature (Aguinaldo and Chambers, 2009; Anz et al., 2010; Fleisig et al., 1995; Werner et al., 1993). The magnitude of the valgus torque in the elbow of the pitchers in this study is consistent with prior literature and, similar to other studies, suggests the UCL is nearing failure point compared to cadaveric studies (Buffi et al., 2015; Morrey and An, 1983; Werner et al., 1993). Additionally, the magnitude and significance of the bilateral difference in the UCLs of baseball pitchers (Table 3, Figure 1) continues to suggest that the overhead throwing motion used in baseball pitching is responsible for the decreased material stiffness seen in the throwing arm of pitchers.

Further research is needed to explore which mechanical factors of the pitching motion are related to the bilateral differences in the material stiffness of the UCL. Examining pitchers across a wider age range, it is possible that the age and amount at which they begin pitching may play a large role in the chronic changes of the UCL as pitching workload in youth pitchers is significantly related to a number of arm injuries (Agresta et al., 2019; Lyman et al., 2011; Makhni et al., 2015; Yang et al., 2014). It is also possible that the timing, intensity and frequency of a pitcher's throwing program varies within our sample and may cause a variety of changes in the material properties of the UCL. Controlling this across a sample may provide additional understanding of the effect of the frequency and intensity of loading on the UCL. With regard to kinetics, the rate of valgus loading of the medial elbow or the valgus angular impulse during the dynamic portions of the pitching motion may provide insight into relationships between the loading of the elbow and the changing material properties of the UCL. Finally, several kinematic factors have been related to valgus torque during the pitching motion such as maximum shoulder external rotation, maximum elbow flexion, elbow flexion at the instant of peak valgus, and elbow flexion at ball release (Aguinaldo and Chambers, 2009). The current research also only examined fastballs. Perhaps examining the range of elbow valgus torques across different pitch types would lend more insight as other pitch types have been shown to have varying kinetics and kinematics (Escamilla et al., 1998). Given the presence of the bilateral difference in UCL stiffness, all of these various factors should be examined in future research to better understand which factors during the pitching motion (or career) are responsible for the large decrease in material stiffness of the UCL observed in the throwing arms of adult baseball pitchers.

In the shoulder, we anticipated finding increased material stiffness in the muscles and tendons of the throwing shoulder in pitchers whose throwing motion generates greater distractive forces at the shoulder joint, knowing that the supraspinatus, infraspinatus, and biceps long head are all loaded eccentrically at high rates of speed and at extended lengths during the arm deceleration phase. However, the results of this research demonstrated relationships between increased peaks and averages in several shoulder kinetic variables and ***decreased*** material stiffness of shoulder soft-tissue structures. This finding is inverse of the hypothesizes relationship. This decreased material stiffness may in fact be showing the evidence of increased microtrauma present in the structures of the shoulder in response to increased loading without enough time to recover, rather than a chronic adaptation to being eccentrically loaded as was hypothesized in this study. This is supported by research suggesting that decreased material stiffness of posterior shoulder muscles is related to the incidence of shoulder pain, again perhaps representing increased tissue degradation (Kobayashi et al., 2019). Additionally, it is of note that the imaging performed for this research was performed during a pre-season period in which the pitchers were actively training and pitching, although pitchers had not pitched in the 48 hours prior to the ultrasound elastography sessions.

Future research should be performed to evaluate the pre-season baseline stiffnesses of these structures during an off-season imaging session when pitchers are not throwing. Understanding the baseline values for an individual pitcher would allow for the determination of how pitching has caused the material properties of his tissues to change and also how well the pitcher is or is not recovering between bouts. Additionally, short-term, longitudinal imaging would be useful to investigate the recovery time needed for shoulder structures to return to baseline values after a pitching bout in order to establish guidelines for the timing of ultrasound elastography sessions with baseball pitchers. It is also of note that while all participants in this research were competitive baseball pitchers, some were starting pitchers and others were relievers which could lead to discrepancies in historical workload across the sample. Additionally, the pitchers used in this research were non-homogenous with regard to their exact level of competition or number of years competing at levels above high school. For example, a college freshman may display different property changes than a senior who has been training and competing at that level for a longer amount of time. Future research should be performed to understand the direction and magnitude of adaptations in the material properties of soft-tissues in young adult pitchers, similar to the prior work on structural properties of the UCL (Atanda et al., 2015). Lastly, only fastballs were evaluated in this research. Pitchers may display altered kinetics and kinematics throwing off-speed pitches, and relationships between tissue properties and mechanics while throwing other pitch types should be evaluated.

Conclusion

This research continues to demonstrate relationships between the mechanics of the overhead pitching motion and the material properties of critical soft-tissue structures of the throwing arm. Increased material stiffness in the supraspinatus muscle and infraspinatus tendon, and decreased material stiffness of the UCL in the throwing arm demonstrate the effect of the repeated exposure of these structures to the high loads of pitching. No relationship was seen between elbow kinetics and UCL properties, possibly suggesting that conventional elbow kinetics may not be the best metric for understanding the impact of pitching on the health of the UCL. Pitchers with elevated shoulder kinetics during the most dynamic portions of the pitching motion displayed decreased material stiffness in critical shoulder structures. This continues to suggest that repeated exposure to such high loads as those seen during the arm-cocking and deceleration phases of the pitching motion may lead to the development of microtrauma in the muscles and tendons responsible for maintaining the structural integrity of the throwing shoulder in pitchers.

CHAPTER 4: RELATIONSHIPS BETWEEN RANGE OF MOTION DEFICITS AND THE MATERIAL STIFFNESS OF CRITICAL SOFT-TISSUE STRUCTURES IN THE THROWING ARMS OF BASEBALL PITCHERS.

Introduction

Adaptations in the range of motion of the throwing shoulder in baseball pitchers as a result of repeated exposure to the high torques created during the pitching motion are well documented in previous literature. Experienced pitchers commonly display increased shoulder external rotation, decreased shoulder internal rotation, and decreased shoulder flexion in their throwing arm compared to their non-throwing arm (Camp et al., 2017; Chant et al., 2007; Pexa et al., 2019; Wilk et al., 2015, 2011, 2004). These adaptations in range of motion in the throwing arms of baseball pitchers are believed to be significant risk factors for upper extremity injury in pitchers over the course of the subsequent season (Camp et al., 2017).

A loss of internal rotation in the throwing shoulder of 20° compared to the non-throwing arm has been termed glenohumeral internal rotation deficit (GIRD) and was initially suggested to be the cause of specific shoulder injuries in baseball pitchers (Burkhart et al., 2003). Further research has proposed that simply the presence of GIRD may not be the greatest risk for injury. The changes in the rotational capability of the shoulder appear to be a posterior shift in the location of the functional range of motion rather than a pure loss of mobility, and pitchers often display a total rotational range of motion (TRM) in their throwing shoulder within 5° of their non-throwing arm (Wilk et al., 2004). This increase in external rotation may be a protective adaptation as increases in external rotation are associated with decreased peak stresses at both the shoulder and elbow during pitching (Hurd and Kaufman, 2012). The posterior shift may also be a result of increased humeral head retroversion in the throwing arm of baseball pitchers, which has been previously correlated with decreased internal rotation and increased external rotation in adult baseball pitchers (Chant et al., 2007). In situations in which the pitcher does in fact demonstrate bilateral deficits greater than 5° of TRM, they are 2.5 times more likely to suffer an injury to their throwing shoulder in the following baseball season (Wilk et al., 2011). The difference in injury risk suggests that there may be separate underlying factors contributing towards the posterior shift in the location of the functional range of motion than contribute towards a bilateral deficit in TRM.

Shoulder range of motion deficits have also been linked to increased risk of elbow injuries in baseball pitchers. Shoulder flexion deficits greater than 5° compared to the non-throwing arm were strongly linked to the incidence of elbow injury in the following season, and when evaluated as continuous variables, the risk of elbow injury increased as shoulder flexion decreased in the throwing arm and external rotation deficit increased (Camp et al., 2017; Wilk et al., 2015). While bilateral deficits in shoulder range of motion have been linked to increased injury risk in both the shoulder and elbow, it is not yet known whether these adaptations are related to changes in the material properties of the soft-tissue structures responsible for maintaining joint stability. It is possible that changes in tissue properties promote changes in the range of motion of the shoulder joint, or conversely that tissue property changes are a result from altered range of motion and usage patterns of the tissues.

In addition to the relationship between soft-tissue properties and shoulder range of motion, the role of humeral retroversion, glenohumeral translation, passive glenohumeral stiffness, posterior capsule and soft-tissue tightness and glenoid retroversion in altered shoulder rotational capacity in baseball pitchers must also continue to be considered and evaluated (Chant et al., 2007). Borsa and colleagues provide an example of such an investigation in their evaluation of passive joint stiffness of the shoulder using an instrumented stress device. However, they report that pitchers exhibiting the increases in external rotation range of motion and decreases in internal rotation range of motion outlined above do not demonstrate altered shoulder joint passive stiffness or ability to resist either anterior- and posterior-directed forces. They note that their experimental design was created to primarily test the capsuloligamentous restraints and found that the static stability of the joint is not compromised (Borsa et al., 2006). It should be considered that when baseball pitchers suffer throwing-related shoulder injuries, the joint is normally not in a passive state, and thus injury may be the result of failure of the contractile components (muscles and tendons) to actively resist the torques developed during the throwing motion rather than the capsuloligamentous components.

This directs us to examine relationships between changes in range of motion in baseball pitchers and changes in the structural and material properties of the musculoskeletal tissues of the shoulder. **Thus, the purpose of this research was to identify relationships between range of motion characteristics and the material properties of critical soft-tissue structures in the throwing arms of baseball pitchers.** It has previously been hypothesized that the changes in range of motion develop over time from the repetitive eccentric loading of the posterior shoulder musculature which causes muscle shortening and damage to the contractile elements of the muscle (Lauritzen et al., 2009; Pexa et al., 2019). Experimental reports have shown repeated maximal eccentric loading of muscles to result in elevated material stiffness which can last several days or lead to chronic adaptations (Lacourpaille et al., 2014). For this reason, **we expect to find increased material stiffness in the muscles and tendons of the supraspinatus and infraspinatus in pitchers with GIRD or TRM deficits greater than 5° compared to their non-throwing arm. However, in pitchers with a posterior shift of their shoulder rotational motion without TRM deficits, we expect to find decreased magnitudes of bilateral differences in the material**

stiffness of the UCL and muscles and tendons of the shoulder, due to the association of increased external rotation of the shoulder with decreased peak loading of the shoulder and elbow during the baseball pitching motion**.**

Methods

To examine relationships between range of motion characteristics and material properties of soft-tissue structures in the throwing arm of baseball pitchers, bilateral shearwave ultrasound elastography imaging and a bilateral passive shoulder ROM evaluation was performed on 26 currently competitive adult baseball pitchers. The participants involved in this chapter are the same as those in Chapter 3 and the imaging sessions were the same in both chapters. All participant demographics can be found in Table 7. All pitchers were between the ages of 18-40 and were either currently listed on a competitive baseball roster or had been during the previous season and were free agents at the time of data collection. Additional exclusion criteria for this study included any surgery on their throwing arm in the previous 12 months, or a history of UCL repair or replacement. Pitchers participated in two separate research sessions on separate days; the ROM evaluation was performed during one session and the ultrasound elastography images were collected during the other session. Upon arriving for their first research session, participants provided informed consent, had their height and weight measured, and completed a questionnaire including regarding their demographics, baseball playing and injury history, and recent exercise and throwing loads. Participants also completed the Kerlan-Jobe Orthopaedic Clinic (KJOC) Shoulder and Elbow questionnaire.

Table 7. Baseball Pitcher Participant Demographics

n	26
Height (m)	1.84 ± 0.06
Mass (kg)	86.19 ± 12.36
Age at Collection (yrs)	20.22 ± 1.50
Throwing Arm (L/R)	6 / 20

Participants were instructed not to pitch and to avoid heavy upper-extremity resistance training in the 48 hours prior to either session.

Material stiffness measurements of the supraspinatus muscle and tendon, infraspinatus muscle and tendon, biceps brachii long head (BBLH) muscle and tendon, and UCL were collected from ultrasound elastography images. All imaging was performed using an Aixplorer (Supersonic Imagine, Aix-en-Provence, France) Ultrasound system. Images of each soft-tissue structure of interest were collected in a split screen mode, displaying B-mode (traditional ultrasound) to allow for clear identification of structural parameters of the tissues, and an elastogram (shearwave elastography colormap overlay) for the measurement of the tissue stiffness. Measurements for each outcome measure were taken from three separate images, all displaying sufficient shearwave propagation throughout the entire tissue of interest. All images were taken by a single member of the research team (CC) who has demonstrated Good (ICC = 0.61-0.80) to Excellent (ICC = 0.81 – 1.00) intra-rater reliability for measuring material stiffness of each of the soft-tissue structures of interest in the current study. See Chapter 2 for a detailed description of the imaging protocol and imager reliability metrics.

Bilateral shoulder ROM measurements were performed following a similar methodology as that outlined by Wilk and colleagues (2014). Passive range of motion (PROM) was evaluated for both shoulders upon participant arrival, prior to any warm-up, stretching, or throwing activities. All PROM measurements were taken using a Baseline Digital Inclinometer (Fabrication Enterprises Inc., White Plains, NY). Shoulder internal and external rotation were assessed at 90° of shoulder abduction and in the scapular plane. Participants were laying supine on a treatment table while the examiner passively moved their arm to the end range of motion for each measurement. Each measurement was taken three times and the mean value was recorded.

Statistical analyses were performed in MATLAB (Mathworks INC., Natick, MA) and JMP (SAS Institute, Cary, NC). Bilateral differences in tissue properties and range of motion will be analyzed using dependent sample t-tests. 2-Way Arm x ROM condition mixed-model ANOVAs were performed to evaluate tissue properties in individuals with GIRD, TRM, or shoulder flexion deficits that have been previously identified as injury risk factors. Dependent and independent sample t-tests were performed post hoc to test for significant differences in the throwing and non-throwing arms properties of the clinical range of motion groups for those tissues that demonstrated significant interactions between ARM and ROM condition. Linear regressions were performed to analyze relationships between the material stiffness of each of the soft tissues of interest in the throwing arm and bilateral range of motion deficits in shoulder flexion, external rotation, and internal rotation, and total rotational motion as continuous variables. Additional linear regressions were used to analyze relationships between bilateral range of motion deficits and the magnitudes of bilateral differences in the properties of the tissues. In all analyses, statistical significance was determined at $p < 0.05$ and statistical trends were determined at $0.05 < p < 0.10$ (Curran-Everett and Benos, 2004).

Results

Bilateral results for the structural and material properties of each of the soft-tissue structures of interest in all participants are described in detail in Chapter 3. Bilateral results for range of motion measurements taken for the throwing and non-throwing shoulders of all participants are shown in Table 8. The throwing arms of the pitchers displayed decreased internal rotation (47.51 ± 11.58° vs 62.01 ± 9.35°, $p < 0.00001$) and increased external rotation (102.57 ± 11.52° mm vs 92.04 ± 10.98°, $p = .0014$) in the throwing arm compared to the non-throwing arm.

However, the total rotational motion was not significantly different in the throwing arm compared to the non-throwing arm (150.08 ± 14.61° vs 154.05 ± 12.96°, p = .3056). Additionally, no significant differences were seen in the shoulder flexion range of motion between the throwing and non-throwing arms (163.52 ± 6.90° vs 162.97 ± 4.93°, p = .7405).

Table 8. Bilateral Range of Motion in Adult Baseball Pitchers			
	Throwing Arm Mean ± SD	**Non-Throwing Arm Mean ± SD**	**p Value**
Internal Rotation	**47.51 ± 11.58**	**62.01 ± 9.35**	**0.00001**
External Rotation	**102.57 ± 11.52**	**92.04 ± 10.98**	**0.0014**
Total Rotational Motion	150.08 ± 14.61	154.05 ± 12.96	0.3056
Shoulder Flexion	163.52 ± 6.90	162.97 ± 4.93	0.7405

Out of the 26 pitchers included in this research, 9 had glenohumeral internal rotation deficits (GIRD) > 20°, 12 had total rotational motion (TRM) deficits > 5°, and 5 had shoulder flexion deficits > 5°, with some pitchers falling into multiple of these ROM classifications. Data comparing the tissue properties of participants with and without the GRID, TRM, and shoulder flexion clinical injury risk factors are shown in Tables 9 and 10. Bilateral results for the structural and material properties of each of the critical soft-tissue structures of interest are displayed in Table 9. Table 10 shows the results of the 2-Way Mixed Model Arm x ROM condition ANOVAs were performed to understand the interaction of each of GIRD, TRM, or shoulder flexion deficits on the tissue properties of the arms. A main effect for Arm was found for several soft-tissue properties, in line with the bilateral results previously described.

Main effects were found for both GIRD and TRM for supraspinatus muscle stiffness (p = 0.0369, p = 0.0470) and a trend towards a main effect for both GIRD and TRM was found for UH joint space under valgus load (p = 0.0849). A significant interaction was found between Arm and GIRD for supraspinatus tendon stiffness (p = 0.0308), showing that individuals with GIRD had a significantly larger bilateral difference than individuals without GIRD (Figure 14). Post hoc tests revealed a significant decrease in the throwing arm supraspinatus tendon stiffness compared to the non-throwing arm in pitchers with GIRD ($p = 0.0129$), however there was not a bilateral difference in pitchers without GIRD ($p = 0.9748$). Post hoc analyses also showed a significant difference across groups in the supraspinatus tendon of the non-throwing arm in pitchers with and without GIRD ($p = .0088$). A significant interaction was also found between Arm and TRM for UCL stiffness ($p = 0.0056$), showing that the magnitude of the bilateral difference in UCL stiffness appears to be dependent on pitchers presenting with clinical ROM deficits (Figure 15). Post hoc tests revealed significant decreases in the throwing arm UCL stiffness compared to the non-throwing arm in pitchers with ($p = 0.0003$) and without ($p = 0.0018$) TRM deficits, however pitchers with TRM deficits displayed a significantly larger decrease in UCL stiffness in the throwing arm. Similarly, a significant interaction was also found between Arm and shoulder flexion deficits for UCL stiffness ($p = 0.0266$) (Figure 16). Post hoc tests again revealed significant decreases in the throwing arm UCL stiffness compared to the non-throwing arm in pitchers with ($p = 0.0151$) and without ($p = 0.0002$) shoulder flexion deficits, however pitchers with shoulder flexion deficits displayed a significantly bilateral difference in UCL stiffness in the throwing arm.

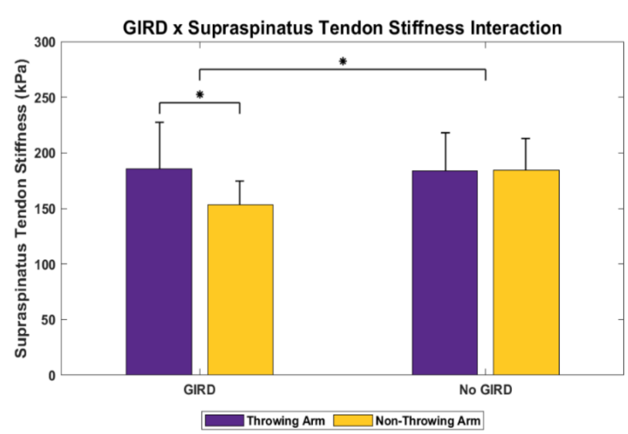


Figure 14. Supraspinatus tendon stiffness in individuals with and without GIRD.

* $p < 0.05$

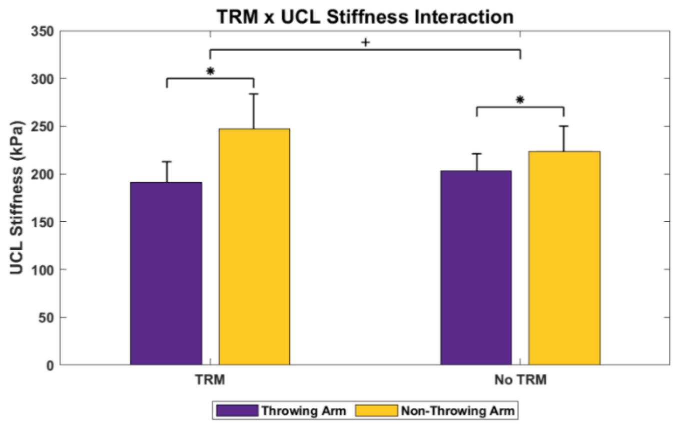


Figure 15. UCL stiffness in individuals with and without TRM deficits.

$* \ p < 0.05; {}^{+}0.05 < p < 0.10$

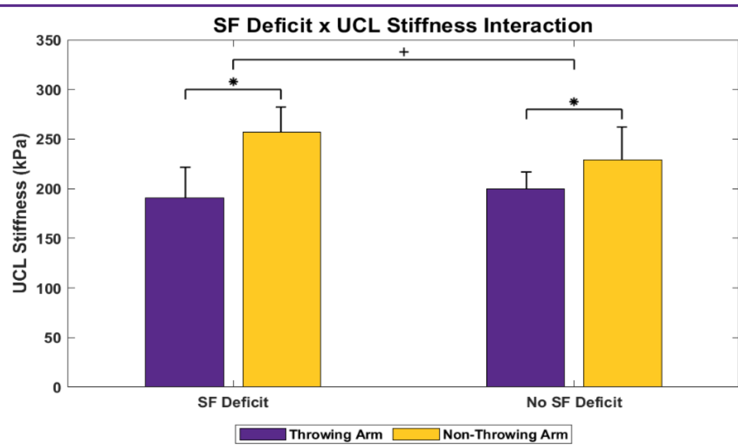


Figure 16. UCL stiffness in individuals with and without shoulder flexion deficits.

$* \ p < 0.05; {}^{+}0.05 < p < 0.10$

Table 9. Bilateral tissue properties in baseball pitchers with range of motion risk factors.								
	GIRD > 20° (n = 9)				No GIRD > 20° (n = 17)			
	Throwing		Non-Throwing		Throwing		Non-Throwing	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
UCL Stiffness (kPa)	192.1	21.9	224.6	33.1	200.7	19.2	239.6	33.0
UCL Length (mm)	21.8	1.8	21.1	1.7	22.3	1.4	21.4	1.3
UH Joint Space - Supported (mm)	4.0	0.5	3.5	0.3	4.4	0.5	3.7	0.6
UH Joint Space - Stressed (mm)	4.7	0.8	3.9	0.3	5.2	0.6	4.3	0.6
UH Joint Space Delta (mm)	0.7	0.4	0.4	0.2	0.8	0.4	0.5	0.2
Supraspinatus Muscle Stiffness (kPa)	30.4	11.0	30.7	9.6	26.6	7.8	21.9	5.4
Supraspinatus Tendon Stiffness (kPa)	185.6	41.7	153.2	21.4	184.0	34.0	184.3	28.6
Infraspinatus Muscle Stiffness (kPa)	23.2	6.9	24.2	8.3	24.9	4.3	21.0	8.6
Infraspinatus Tendon Stiffness (kPa)	211.8	40.7	181.8	40.1	194.4	30.1	170.7	30.9
BBLH Muscle Stiffness (kPa)	38.0	10.4	39.1	9.7	37.2	7.8	35.3	6.4
BBLH Tendon Stiffness (kPa)	71.9	22.5	86.7	30.6	81.2	26.6	80.2	17.3
	TRM Deficit > 5° (n = 12)				No TRM Deficit > 5° (n = 14)			
	Throwing		Non-Throwing		Throwing		Non-Throwing	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
UCL Stiffness (kPa)	191.5	21.5	247.0	36.7	203.1	18.1	223.6	26.5
UCL Length (mm)	21.8	1.8	21.2	1.7	22.4	1.3	21.3	1.2
UH Joint Space - Supported (mm)	4.1	0.5	3.6	0.5	4.3	0.6	3.7	0.5
UH Joint Space - Stressed (mm)	4.8	0.6	4.1	0.4	5.2	0.8	4.2	0.6
UH Joint Space Delta (mm)	0.7	0.3	0.5	0.3	0.8	0.4	0.5	0.2
Supraspinatus Muscle Stiffness (kPa)	30.4	11.3	28.6	9.3	25.8	6.2	21.8	5.6
Supraspinatus Tendon Stiffness (kPa)	184.2	41.9	175.3	36.1	184.8	31.8	172.1	24.9
Infraspinatus Muscle Stiffness (kPa)	25.1	5.6	24.3	9.8	23.6	5.0	20.3	7.0
Infraspinatus Tendon Stiffness (kPa)	205.8	27.3	174.8	35.8	195.9	39.9	174.3	33.8
BBLH Muscle Stiffness (kPa)	37.8	5.9	36.8	8.8	37.2	10.6	36.4	7.1
BBLH Tendon Stiffness (kPa)	72.4	17.2	81.3	17.6	82.8	30.3	83.5	26.5
	SF Deficit > 5° (n = 5)				No SF Deficit > 5° (n = 21)			
	Throwing		Non-Throwing		Throwing		Non-Throwing	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
UCL Stiffness (kPa)	190.6	31.0	256.8	25.5	199.4	17.4	229.1	33.0
UCL Length (mm)	22.7	0.9	22.2	0.9	22.0	1.6	21.1	1.4
UH Joint Space - Supported (mm)	4.0	0.5	3.5	0.1	4.3	0.6	3.7	0.6
UH Joint Space - Stressed (mm)	4.9	0.6	4.0	0.2	5.0	0.7	4.2	0.6
UH Joint Space Delta (mm)	0.9	0.4	0.5	0.1	0.7	0.4	0.5	0.3
Supraspinatus Muscle Stiffness (kPa)	31.9	9.6	28.3	12.6	27.0	8.9	24.1	6.9
Supraspinatus Tendon Stiffness (kPa)	183.8	56.1	160.0	21.9	184.7	31.5	176.8	31.1
Infraspinatus Muscle Stiffness (kPa)	23.5	5.1	23.6	10.6	24.5	5.4	21.8	8.2
Infraspinatus Tendon Stiffness (kPa)	203.5	14.4	161.2	21.4	199.7	37.9	177.7	36.0
BBLH Muscle Stiffness (kPa)	41.9	8.9	36.0	9.2	36.4	8.4	36.7	7.6
BBLH Tendon Stiffness (kPa)	77.9	37.3	70.5	16.6	78.0	22.8	85.3	22.9

TABLE 10. 2-Way ANOVA Results. *p < 0.05; +0.05 < p < 0.10			
	GIRD > 20° (n = 9 / 17)		
	Arm	**GIRD**	**Arm*GIRD**
UCL Stiffness (kPa)	**< 0.0001***	0.191	0.659
UCL Length (mm)	**0.002***	0.481	0.754
UH Joint Space Supported (mm)	**< 0.0001***	0.121	0.519
UH Joint Space Stressed (mm)	**< 0.0001***	**0.085+**	0.562
UH Joint Space Delta (mm)	**0.006***	0.309	0.977
Supraspinatus Muscle Stiffness (kPa)	0.227	**0.037***	0.177
Supraspinatus Tendon Stiffness (kPa)	**0.034***	0.197	**0.031***
Infraspinatus Muscle Stiffness (kPa)	0.406	0.762	0.168
Infraspinatus Tendon Stiffness (kPa)	**0.001***	0.253	0.660
BBLH Muscle Stiffness (kPa)	0.786	0.440	0.347
BBLH Tendon Stiffness(kPa)	0.103	0.879	**0.063+**
	TRM Deficit > 5° (n = 12 / 14)		
	Arm	**TRM**	**Arm*TRM**
UCL Stiffness (kPa)	**< 0.0001***	0.499	**0.006***
UCL Length (mm)	**0.001***	0.530	0.404
UH Joint Space Supported (mm)	**< 0.0001***	0.361	0.578
UH Joint Space Stressed (mm)	**< 0.0001***	0.269	0.415
UH Joint Space Delta (mm)	**0.005***	0.403	0.706
Supraspinatus Muscle Stiffness (kPa)	0.113	**0.047***	0.528
Supraspinatus Tendon Stiffness (kPa)	0.159	0.907	0.805
Infraspinatus Muscle Stiffness (kPa)	0.224	0.216	0.466
Infraspinatus Tendon Stiffness (kPa)	**0.001***	0.667	0.486
BBLH Muscle Stiffness (kPa)	0.560	0.853	0.957
BBLH Tendon Stiffness(kPa)	0.255	0.465	0.329
	SF Deficit > 5° (n = 5 / 21)		
	Arm	**SF Deficit**	**Arm*SF Deficit**
UCL Stiffness (kPa)	**< 0.0001***	0.393	**0.027***
UCL Length (mm)	**0.018***	0.199	0.475
UH Joint Space Supported (mm)	**0.001***	0.226	0.696
UH Joint Space Stressed (mm)	**< 0.0001***	0.561	0.802
UH Joint Space Delta (mm)	**0.006***	0.307	0.431
Supraspinatus Muscle Stiffness (kPa)	0.162	0.223	0.857
Supraspinatus Tendon Stiffness (kPa)	0.102	0.527	0.407
Infraspinatus Muscle Stiffness (kPa)	0.540	0.882	0.513
Infraspinatus Tendon Stiffness (kPa)	**0.001***	0.679	0.230
BBLH Muscle Stiffness (kPa)	0.137	0.515	0.102

The relationships between soft-tissue properties and the range of motion results are displayed in Tables 11-13. Correlation plots for significant correlations are displayed in Figures 14-16. Significant correlations were observed between the throwing arm shoulder flexion and the UCL length in the throwing arm ($r = -0.48$, $p = 0.013$) and throwing arm infraspinatus tendon stiffness and the bilateral difference in shoulder internal rotation ($r = -0.41$, $p = 0.04$). When examining relationships between bilateral differences in tissue properties and bilateral differences in range of motion, significant relationships were found between the supraspinatus tendon and shoulder internal rotation ($r = -0.46$, $p = 0.02$), and shoulder external rotation ($r = 0.52$, $p = 0.01$); as well as for the biceps brachii long head tendon and shoulder internal rotation ($r = 0.50$, $p = 0.01$), and shoulder total rotational motion ($r = 0.45$, $p = 0.02$).

Table 11. Correlation Coefficients between Tissue Properties and Range of Motion in the throwing arm. *p <0.05; ⁑0.05 < p < 0.1

	Internal Rotation	External Rotation	Total Rotational Motion	Shoulder Flexion
UCL Stiffness	**0.420***	-0.140	0.222	**0.425***
UCL Length	0.008	0.125	0.105	**-0.480***
UH Joint Space – Supported	0.147	-0.152	-0.003	0.180
UH Joint Space – Stressed	0.130	-0.125	0.004	0.033
UH Joint Space – Delta	0.024	-0.009	0.012	-0.202
Supraspinatus Muscle	-0.193	0.136	-0.046	-0.283
Supraspinatus Tendon	-0.283	-0.074	-0.283	-0.230
Infraspinatus Muscle	-0.079	-0.063	-0.112	-0.096
Infraspinatus Tendon	**-0.337⁑**	0.009	-0.261	-0.075
BBLH Muscle	0.199	-0.016	0.145	0.015
BBLH Tendon	0.134	-0.136	-0.001	0.242

Table 12. Correlation Coefficients between Throwing Arm Tissue Properties and Bilateral Deficits in Range of Motion. *p <0.05; ⁑0.05 < p < 0.1

	Internal Rotation	External Rotation	Total Rotational Motion	Shoulder Flexion
UCL Stiffness	**0.370 ⁑**	-0.176	0.258	0.183
UCL Length	0.121	0.171	0.276	-0.239
UH Joint Space – Supported	0.123	0.010	0.144	0.224
UH Joint Space – Stressed	0.120	0.014	0.143	0.068
UH Joint Space – Delta	0.041	0.011	0.054	-0.201
Supraspinatus Muscle	-0.184	0.181	-0.049	-0.229
Supraspinatus Tendon	-0.232	0.278	-0.021	-0.122
Infraspinatus Muscle	0.102	-0.170	-0.031	0.091
Infraspinatus Tendon	**-0.407***	**0.339 ⁑**	-0.162	-0.105
BBLH Muscle	0.026	0.198	0.195	-0.145
BBLH Tendon	0.328	-0.016	**0.347 ⁑**	0.064

Table 13. Correlation Coefficients between Bilateral Deficits in Tissue Properties and Bilateral Deficits in Range of Motion. *p <0.05; ⁑0.05 < p < 0.1

	Internal Rotation	External Rotation	Total Rotational Motion	Shoulder Flexion
UCL Stiffness	0.099	**0.362⁑**	**0.413***	0.144
UCL Length	0.039	0.084	0.114	-0.007
UH Joint Space – Supported	0.118	0.029	0.154	0.166
UH Joint Space – Stressed	0.072	0.102	0.164	0.060
UH Joint Space – Delta	-0.053	0.096	0.022	-0.128
Supraspinatus Muscle	0.267	-0.037	0.262	-0.090
Supraspinatus Tendon	**-0.461***	**0.518***	-0.071	-0.280
Infraspinatus Muscle	0.252	-0.260	0.057	0.317
Infraspinatus Tendon	-0.162	0.127	-0.071	-0.173
BBLH Muscle	0.032	0.008	0.042	-0.224
BBLH Tendon	**0.501***	-0.120	**0.448***	-0.112

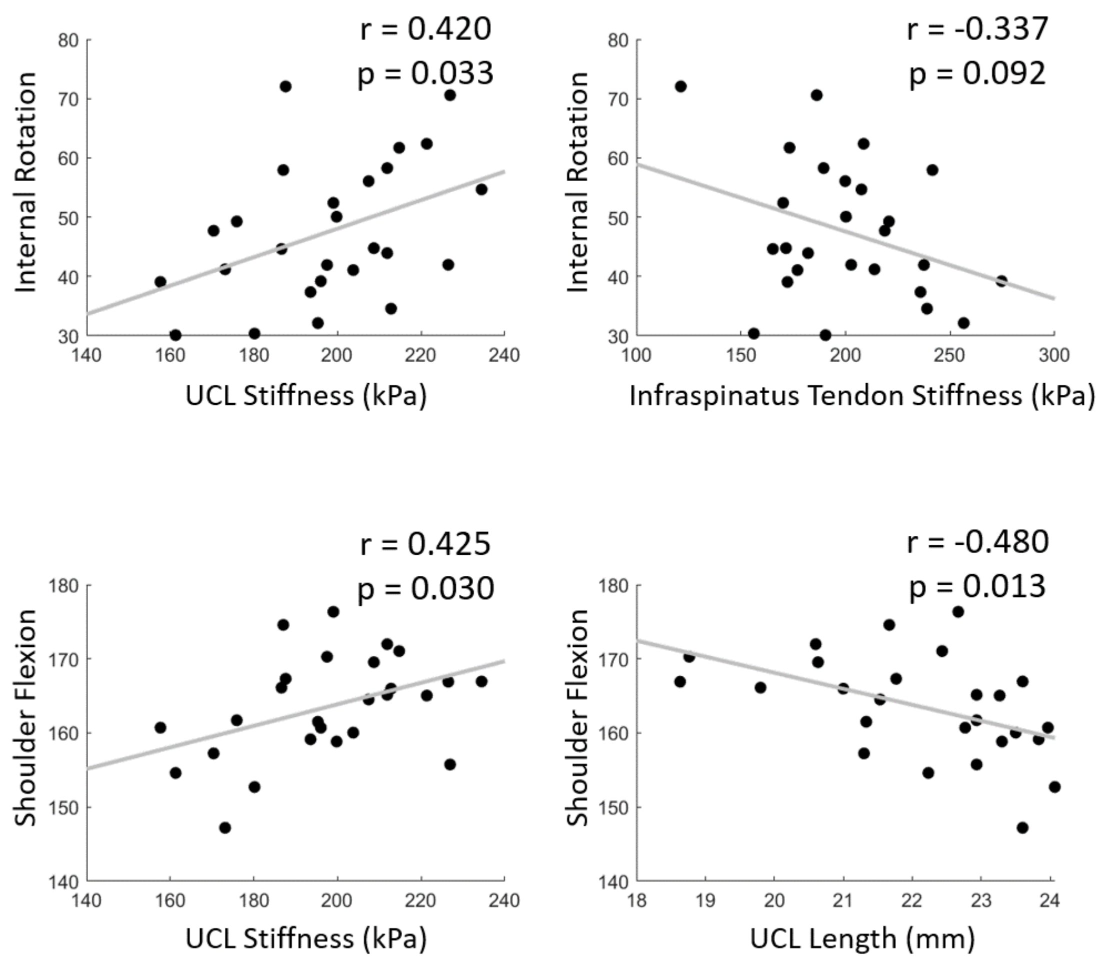


Figure 17. Significant correlations between tissue properties in the throwing arm and throwing arm shoulder range of motion.

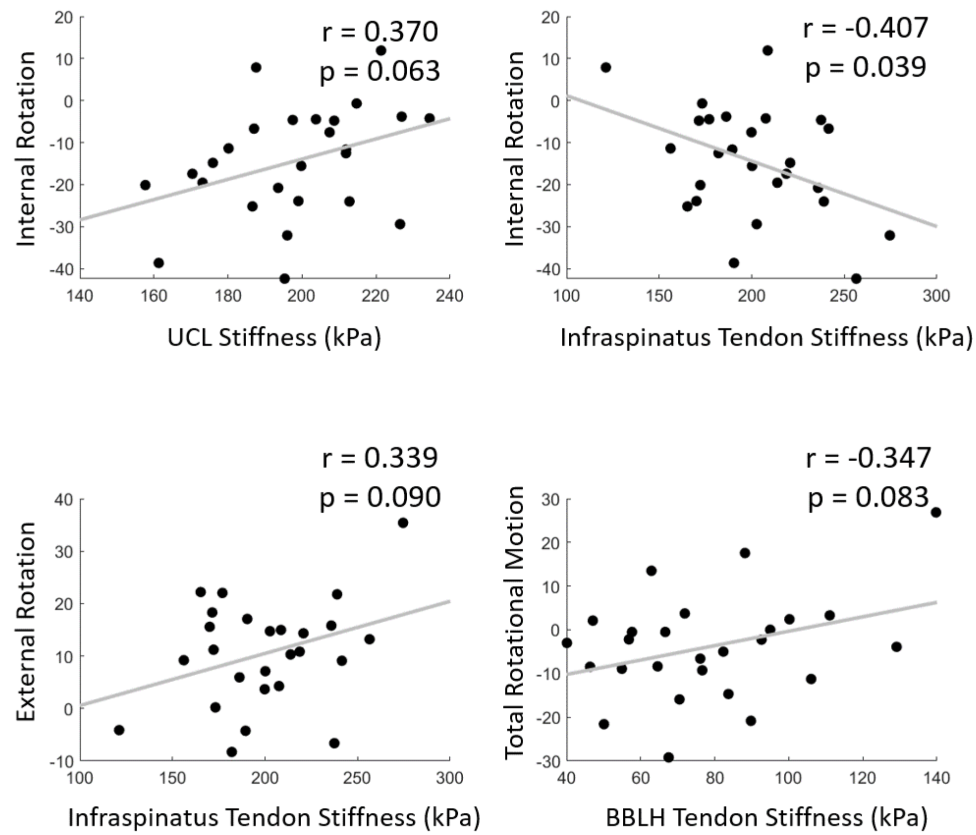


Figure 18. Significant correlations between tissue properties in the throwing arm and bilateral deficits in shoulder range of motion.

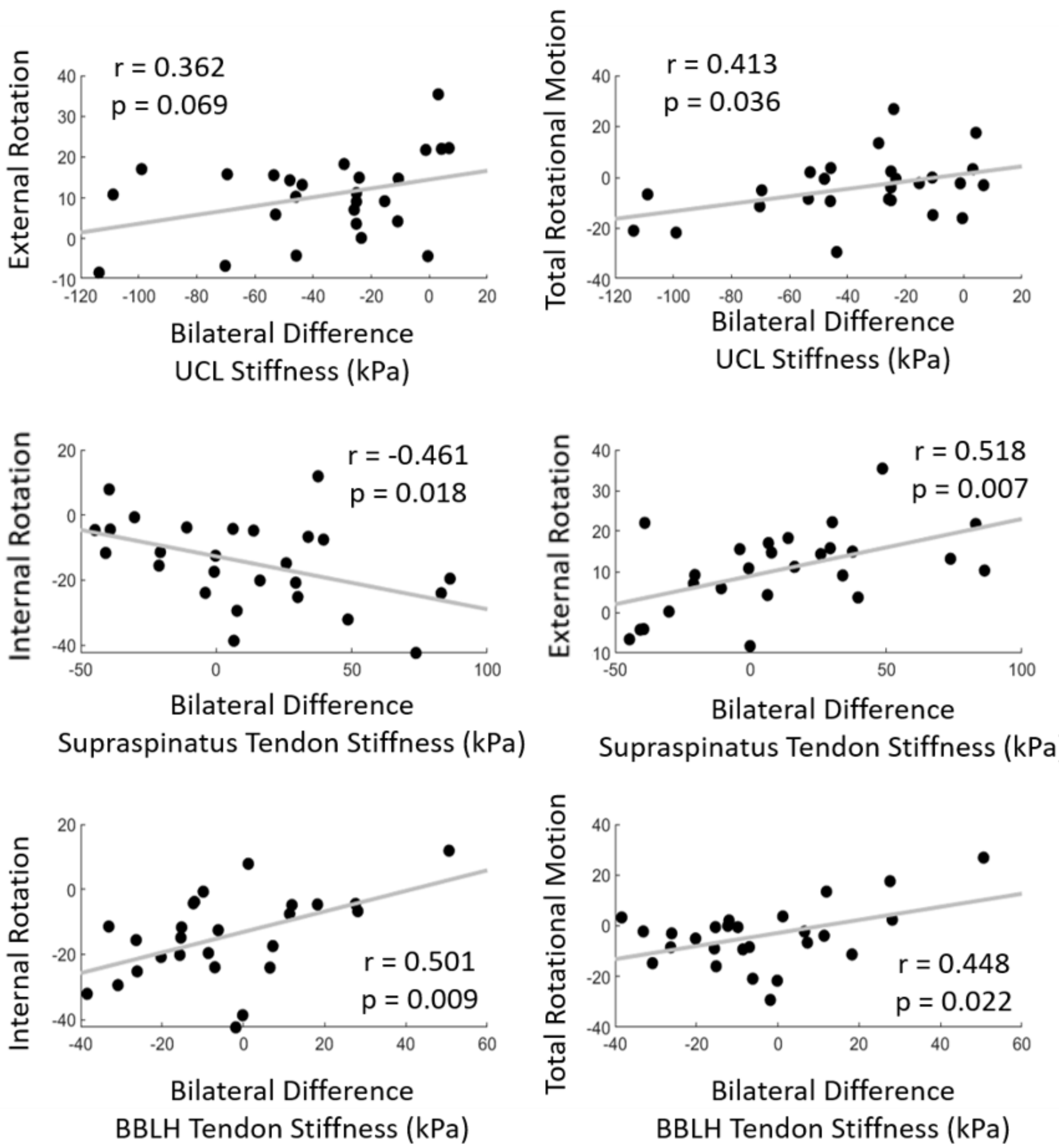


Figure 19. Significant correlations between bilateral differences in tissue properties and bilateral deficits in shoulder range of motion.

Discussion

This research is the first to examine relationships between the structural and material properties of commonly injured soft-tissue structures in the arms of baseball pitchers and bilateral deficits in shoulder range of motion. Understanding these relationships is important for gaining more clarity about the specific mechanism of soft-tissue injuries as specific range of motion deficits have been identified as future injury risk factors. Glenohumeral internal rotation range of motion deficits greater than 20° and total shoulder rotational motion deficits greater than 5° have been reported to be indicative of elevated future injury risk in the throwing arms of baseball pitchers (Burkhart et al., 2003; Camp et al., 2017; Wilk et al., 2015, 2004).

Our results demonstrating decreased internal rotation and increased external rotation in the throwing arms are in agreement with numerous previous research studies examining bilateral ROM differences in baseball pitchers (Burkhart et al., 2003; Wilk et al., 2015, 2011). Additionally, the presence of significant differences in internal and external rotation without a significant difference in bilateral total rotational motion across the entire sample is also consistent with previous research describing the changes in shoulder range of motion as a posterior shift in rotational motion rather than a loss or gain of range of motion (Wilk et al., 2011).

The results are novel in demonstrating a main effect for GIRD and supraspinatus muscle stiffness without an association between arm and tissue stiffness or an interaction between arm and GIRD. When discussing this result, it is important to understand that it is unlikely that the tissue properties of the non-throwing arm are altered as a result of baseball pitching, so they are likely a reflection of the native state of the throwing arm. Interpreting this result while considering the mean values from Table 9, it appears that individuals with naturally elevated supraspinatus muscle stiffness are more likely to develop GIRD with baseball pitching, as both the non-throwing and throwing arms displayed elevated supraspinatus muscle stiffness in pitchers with GIRD compared to pitchers without GIRD. The same association is present for TRM deficits, again suggesting that pitchers with increased stiffness in the supraspinatus muscle prior to baseball may be at a greater risk of developing TRM deficits once they begin competitively pitching at high levels.

Contrary to what we see in muscle, our results suggest that individuals with lower tendon stiffness in the supraspinatus of the non-throwing arm may also be at an increased risk of developing GIRD. The supraspinatus tendon stiffness in the throwing arm appears similar in pitchers with and without GIRD, however there was a dramatic difference in the material stiffness in the non-throwing arm, with pitchers with GIRD having much lower stiffnesses. Post hoc analyses show a significant difference in the supraspinatus tendon of the non-throwing arm in pitchers with and without GIRD (153.25 ± 21.41 kPa vs 184.30 ± 28.60 kPa, $p = .0088$). This suggests pitchers with naturally decreased supraspinatus tendon stiffness are susceptible to much greater increases in the stiffness of the tendon in the throwing arm, and thus also of developing GIRD. However, it is not yet known if the loss of ROM or suggested increase in tissue material stiffness occurs first and whether or not one causes the other. Conceptually, it makes sense that an external rotator that is significantly less pliable in the throwing arm than the non-throwing arm would contribute to the loss of internal rotation in the throwing arm compared to the non-throwing arm.

In all three range of motion classifications, we see a main effect of arm for UCL stiffness, with the material stiffness of the UCL in the throwing arm being less stiff than the non-throwing arm. This is expected and has been seen across entire samples of healthy pitchers. For TRM and shoulder flexion deficits we also see significant interactions between arm and clinical range of motion classification. The UCL of the non-throwing arms of pitchers with TRM as well as pitchers with shoulder flexion deficits was much stiffer than the non-throwing arm in pitchers without the ROM deficits, however the UCLs of the throwing arms were similar across all groups. Similar to the supraspinatus tendon in pitchers with GIRD, post hoc analyses suggest this interaction may be due to the difference between the non-throwing arms of the pitchers with and without TRM (247.03 ± 36.72 kPa vs 223.60 ± 26.54 kPa, p = .0717), and shoulder flexion deficits (256.77 ± 25.49 kPa vs 229.09 ± 33.05, p = .0941). This again suggests that the ROM deficit may be linked to having significantly different, in this case higher, material stiffness prior to heavy competitive pitching loads compared to other pitchers. The loads experienced by the elbow cause changes in the UCL of the throwing arm, and it appears those changes (magnitude of bilateral difference) are heightened in pitchers with ROM deficits in the shoulder. This change, as opposed to the ones described previously in the supraspinatus, may be a result of continuing to pitch with ROM deficits, as opposed to shoulder ROM deficits being caused by the material stiffness of the UCL. One potential explanation of this unexpected finding is that pitching with shoulder ROM deficits causes greater decreases in UCL material stiffness, which is believed to be indicative of tissue degradation and microdamage. Those pitchers who had non-throwing arm (and native throwing arm) UCL stiffnesses that are lower *and* have shoulder ROM deficits may have already suffered significant UCL injuries such as partial or full-thickness tears, and thus were excluded from this study.

When interpreting the results from the 2-way ANOVAs, we will be considering the state of the non-throwing arm to be the healthy, pre-pitching baseline status of the throwing arm. While there are certainly many assumptions with this, there is not a universal baseline value for the properties of soft tissues across individuals and understanding the unilateral nature of the loading experienced during the baseball pitching motion, this is the best possible method.

Several of the linear regression findings are of note as they provide conceptual understanding of the relationships between soft-tissue material properties and range of motion as a continuous variable rather than only within the bounds of clinical diagnoses. The relationship between increasing UCL stiffness of the throwing arm and throwing arm shoulder flexion seems to provide some context to previously reported injury risk factors. Multiple prospective studies have reported shoulder flexion deficits in the throwing arm greater than 5° as placing a pitcher at significantly greater risk of a UCL tear. Knowing that the UCL demonstrates decreased material stiffness in the throwing arms of even asymptomatic adult pitchers as a result of the loading of the pitching motion, it makes sense that decreasing throwing arm shoulder flexion would be related to even larger decreases in UCL stiffness.

Additionally, increased infraspinatus tendon stiffness being related to decreasing shoulder internal rotation as continuous variables support the findings of the categorical test described previously. Increasing material stiffness of a primary external rotator tendon should lead to a decrease in the internal rotation capability of the shoulder. Pairing this finding with our knowledge of increased material stiffness of the posterior shoulder structures in the throwing arm, this result continues to support the belief that individuals with naturally higher material stiffness of the external rotators are at elevated risk for having clinically meaningful internal rotation deficits. Examining relationships between bilateral differences in tissue properties and range of motion deficits this relationship can be seen again in the supraspinatus tendon. Our results demonstrate a relationship between an increasing bilateral difference in tendon stiffness and increasing internal rotation deficit. This means that as the throwing arm supraspinatus tendon presented with increasingly greater stiffness in comparison to the non-throwing arm, the throwing arm had a greater magnitude of the deficit in internal rotation. Along the same implication as the loss of internal rotation, as the magnitude of bilateral difference of supraspinatus tendon stiffness increased, the magnitude of bilateral difference in external rotation also increased with the throwing arm have a greater increase in external rotation. This continues to demonstrate that increasing stiffness of external rotators is associated with decreased internal rotation and increased external rotation of the shoulder, which may become injury risk factors if the changes become clinically meaningful.

There are some limitations that should be acknowledged in this research. In order to have a more complete understanding of the causation of material property changes in the tissues of the shoulder as they relate to range of motion changes, longitudinal studies should be performed rather than cross-sectional as performed here. Longitudinal tracking of both tissue properties and range of motion would allow for an understanding of whether range of motion changes are occurring prior to or after changes in the material properties of critical soft-tissue structures. This may add to the explanation of range of motion changes above what can be explained by humeral torsion in the throwing arm. Additionally, the pitchers used in this research were non-homogenous with regard to their exact level of competition or number of years competing at levels above high school. The inability for the imaging session to confidently explain baseline tissue properties is a limitation of this research. Future research should be performed to evaluate the normative stiffnesses of these structures during an off-season imaging session when pitchers are not throwing. Finally, the post-hoc examinations within the GIRD, TRM, or SF deficit groups may have been underpowered as a result of the small samples within each group.

Conclusion

This research continues to strengthen and add to the understanding of the effects of baseball pitching on bilateral range of motion of the shoulder. In addition to confirming several prior research studies demonstrating increased external rotation and decreased internal rotation of the shoulder in adult baseball pitchers, this research was the first to examine relationships between the material properties of soft-tissue structures in the shoulder and range of motion. Increasing stiffness of external rotators, such as the supraspinatus and infraspinatus tendons was correlated in decreasing internal rotation and increasing external rotation. Additionally, loss of shoulder flexion range of motion was related to decreasing stiffness of the UCL in the throwing arm, perhaps explaining the relationship between shoulder flexion loss and UCL injury. Finally, it is reasonable to believe that the material properties of the non-throwing arm are important indicators of a pitchers' baseline tissue properties and may provide insight into the likelihood of a pitcher to present with a clinical range of motion risk factor such as GIRD, TRM deficit, or shoulder flexion deficit. Future research understanding the ability of targeted interventions to alter the material properties of critical soft-tissue structures may help decrease the number of pitchers that present with ROM deficit injury risk factors.

CHAPTER 5: DISCUSSION

The research studies described in this report provide new insight into the effect of baseball pitching on critical structures in the throwing arms of pitchers. This report is novel in describing a single, comprehensive method for the visualization and quantification of the material properties of the UCL, and supraspinatus, infraspinatus, and biceps brachii long head muscles and tendons. Additionally, describing relationships between the soft-tissue properties in the arm and previously described injury risk factors in a pitcher’s mechanics and in their shoulder range of motion provides a new depth of understanding to the field of medical and training professionals working with baseball pitchers.

This research expands on the growing body of scientific literature demonstrating the influence of baseball pitching on the structural and material properties of critical soft-tissue structures in the throwing arms of baseball pitchers. In the past 25 years, a large body of research has developed examining the structural properties of structures such as the UCL in pitchers. Bilateral differences have been reported in both injured and asymptomatic pitchers demonstrating the effect of the large loads experienced during pitching on the UH joint space and the length, thickness, and cross-sectional areas of soft-tissues in the shoulder and elbow (Ciccotti et al., 2014; Nazarian et al., 2003; Pexa, 2015; Sasaki et al., 2002). However, these changes have not yet been related to increased risk of future injury in adult pitchers. This has led researchers more recently to focus on examining the material properties of the tissues, such as material stiffness.

This research adds to this new body of literature describing how pitching is influencing not only the structural, but also the material properties of the structures of the throwing arm as there were several bilateral differences in the shoulder and elbow. Aligning with other recent research, our results demonstrate increased medial elbow laxity and decreased material stiffness of the UCL in the throwing arm compared to the non-throwing arm. This adaptation showing increased medial elbow laxity is supported by our results of increased UH joint space under valgus load and the delta UH joint space from rest to valgus-loaded in the throwing arm compared to the non-throwing arm, a finding commonly reported in imaging studies of the medial elbow in baseball pitchers (Atanda et al., 2015; Bica et al., 2015; Ciccotti et al., 2014; Curran et al., 2016; Nazarian et al., 2003; Sasaki et al., 2002). While UH joint space may be a helpful description of the overall integrity of the medial elbow, it is a measure of the global stability of the elbow joint rather than of the UCL specifically. UCL stiffness may be a more specific proxy for the health of the ligament itself. Overall, we found increased material stiffness in the muscles and tendons of both the supraspinatus and infraspinatus in the throwing arm compared to the non-throwing arm. Specifically, the infraspinatus tendon was significantly stiffer, and the supraspinatus muscle trended towards having increased material stiffness in the throwing shoulders of baseball pitchers.

It is also important to consider the bilateral imaging data included in Appendix C when considering the impact of a reliable imaging methodology. In a sample of 16 healthy adult males who are not overhead throwing athletes, the only tissue property that showed significant bilateral difference between the throwing and non-throwing arms was the length of the UCL. All other tissue properties including the material stiffness of the supraspinatus, infraspinatus, and BBLH muscles and tendons, as well as the stiffness of the UCL and the UH joint space at rest and under a valgus load. This is an important finding as it supports the belief that significant bilateral differences in most tissue properties in baseball pitchers result from the dramatic loads placed on the structures of the throwing arm during the pitching motion. This has commonly been reported in much of the imaging literature surrounding the bilateral differences observed in UCL properties, but is now supported by comprehensive evidence encompassing both the shoulder and the elbow (Atanda et al., 2015; Ciccotti et al., 2014; Nazarian et al., 2003; Sasaki et al., 2002).

The UCL adaptation showing decreased material stiffness was expected based on prior research in our lab during off-season measurement (Curran et al., 2016). The bilateral differences in the shoulder showing increased material stiffness in the throwing arm was also hypothesized based on prior research showing increased material stiffness lasting more than 21 days in response to eccentric loading experienced by the musculoskeletal structures while at an already extended length (Lacourpaille et al., 2014). The posterior shoulder soft-tissue structures in this research are in such a position as they work to maintain shoulder posture and resist shoulder anterior force during the arm deceleration phase of the pitching motion. These results support the belief that chronic pitching is causing accumulating microtrauma as a result of repeated exposure to very high loads during the throwing motion.

In addition to chronic adaptation presented as bilateral differences in tissue properties, this research also demonstrated that the changes taking place in the properties of soft-tissues of the throwing arm are related to both the kinetics of the throwing motion as well as a pitcher's range of motion. This is particularly important as kinetic factors and range of motion deficits are two factors that have been shown to prospectively be related to increased injury risk in adult baseball pitchers. Understanding the relationship between throwing mechanics or range of motion deficits and the material stiffness of specific structures in the throwing arm may provide new insight into specific injury mechanisms in baseball pitchers.

The results of this dissertation show that specific kinetics of the throwing motion seem to be responsible as modulators of the changes in material stiffness seen in the throwing arm. Elevated shoulder compression and shoulder external rotation kinetics were moderately related to decreased material stiffness in posterior shoulder tendons, as well as the biceps brachii muscle belly and long head tendon. This result supports the common belief among researchers that most soft-tissue injuries in the throwing arms of baseball pitchers are in fact acute manifestations of chronic microdamage as a result of the extreme loading placed on the structures of the throwing arm. Decreased material stiffness in these structures may be a result of tissue degradation due to recent pitching bouts, explaining why increased kinetics would be related to lower stiffnesses.

We also expected to find a relationship between elbow kinetics during the baseball pitching motion and UCL stiffness. However, none of the seven kinetic factors examined in this research were related to either the throwing arm UCL stiffness or the bilateral difference in UCL stiffness. This finding is not in agreement with our central hypothesis or the commonly accepted beliefs among researchers about the effect of the elbow valgus load during the arm-cocking phase of the pitching motion on the ligament. The magnitude and consistency of the bilateral difference in the UCLs of baseball pitchers continues to suggest that the overhead throwing motion used in baseball pitching is responsible for the decreased material stiffness seen in the throwing arm of pitchers, although other relationships or factors may need to be examined. One consideration is that it is unknown whether the processing software used in this analysis, Visual 3D, adjusts marker placement to fit its rigid models, which would change the degree to which an individual presents with humeral torsion. A pitcher having significant humeral torsion may alter the way the X and Y axes should be oriented around the longitudinal axis of the humerus during a static calibration, perhaps shifting the elbow valgus torque curve. It is possible that other factors regarding an individual's pitching history or mechanics may provide a better insight into the effect of pitching on the UCL. For example. examining pitchers across a wider age range, it is possible that the age and amount at which they begin pitching may play a large role in the chronic changes of the UCL as pitching workload in youth pitchers is significantly related to a number of arm injuries (Agresta et al., 2019; Lyman et al., 2011; Makhni et al., 2015; Yang et al., 2014). Also, the current research also only examined fastballs. Perhaps examining the range of elbow valgus torques across different pitch types would lend more insight as other pitch types have been shown to have varying kinetics and kinematics (Escamilla et al., 1998). Regarding kinetics, the rate of valgus loading of the medial elbow or the valgus angular impulse during the dynamic portions of the pitching motion may provide insight into relationships between the loading of the elbow and the changing material properties of the UCL. Finally, several kinematic factors have been related to valgus torque during the pitching motion such as maximum shoulder external rotation, maximum elbow flexion, elbow flexion at the instant of peak valgus, and elbow flexion at ball release (Aguinaldo and Chambers, 2009). All these various factors should be examined in future research to better understand which factors during the pitching motion (or career) are responsible for the large decreased in material stiffness of the UCL observed in the throwing arms of adult baseball pitchers.

As many researchers have previously hypothesized that the injury risk in baseball pitching comes from the repeated exposure to the extreme forces and torques experienced during the pitching motion, the relationships between mechanics and tissue property changes would serve to support that notion. One area in which this injury risk has presented itself in previous literature has been in bilateral deficits in shoulder range of motion. This research is also the first to identify and describe relationships between range of motion injury risk factors and material properties of soft-tissue structures in the arm. Using the non-throwing arm to reflect the native state of the throwing arm, our results suggest that individuals with naturally elevated posterior shoulder muscle stiffness are more likely to develop GIRD with baseball pitching, as both the non-throwing and throwing arms displayed elevated stiffness in pitchers with GIRD compared to pitchers without GIRD. The same association is present for TRM deficits. If non-throwing arm properties represent the native state of the throwing arm, again suggesting that pitchers with increased muscle stiffness prior to becoming competitive baseball pitchers may be at a greater risk of developing TRM deficits once they begin competing at high levels. The differences between pitchers with clinical deficits in range of motion and those without actually appear to actually be focused on the non-throwing arm. Pitchers with GIRD or TRM displayed larger magnitudes of bilateral differences in material properties, yet the throwing arm properties were similar to pitchers that didn't have GIRD or TRM deficits. Assuming the non-throwing arm is representative of an individual's baseline, pre-pitching state, it is worth investigating whether the non-throwing arm can be used to identify pitchers who may present with clinical range of motion deficits.

Furthermore, our data suggests that individuals with naturally lower material stiffness in the posterior shoulder tendons may also be at an increased risk of developing GIRD as adult pitchers. In pitchers with and without GIRD, the tendon stiffness in the throwing arm appears similar, however there was a dramatic difference in the material stiffness in the non-throwing arm with pitchers with GIRD having much lower stiffnesses. This suggests pitchers with naturally decreased tendon stiffness are susceptible to much greater increases in the stiffness of the tendon in the throwing arm, and thus also of presenting with GIRD. Having increased stiffness in external rotators of the throwing arm would contribute to the loss of internal rotation seen in pitchers.

The UCL of the non-throwing arms of pitchers with TRM as well as pitchers with shoulder flexion deficits trended to be stiffer than the non-throwing arm in pitchers without the ROM deficits, however the UCLs of the throwing arms were similar across all groups. This again suggests that the ROM deficit may be linked to having significantly different, in this case higher, material stiffness prior to heavy competitive pitching loads compared to other pitchers. The loads experienced by the elbow cause changes in the UCL of the throwing arm, and it appears those changes (magnitude of bilateral difference) are heightened in pitchers with ROM deficits in the shoulder. This change, as opposed to the once described previously in the supraspinatus, may be a result of continuing to pitch with ROM deficits, as opposed to shoulder ROM deficits being caused by the material stiffness of the UCL. If pitching with shoulder ROM deficits causes greater decreases in UCL material stiffness, it is possible that pitchers who had lower non-throwing arm UCL stiffnesses reflective of lower throwing arm native UCL stiffness and have shoulder ROM deficits may have already suffered significant UCL injuries.

The relationships shown in this research between previously identified mechanical and range of motion risk factors and the material stiffness of critical soft-tissue structures in the throwing arms of adult baseball pitchers have potentially dramatic implications for future research. Understanding the relationships between material stiffness of tissues that are commonly injured and previously known risk factors suggests the need for the monitoring of these properties as a proxy of tissue health.

The introduction and validation of musculoskeletal SWE in recent years has provided a non-invasive method for visualizing and quantifying both the structural and material properties of musculoskeletal structures in vivo. As most researchers believe that the majority of soft-tissue injuries in the throwing arm of baseball pitchers are acute manifestations of chronic microtrauma (Andrews et al., 1985; Andrews and Angelo, 1988; Buffi et al., 2015; Burkhart et al., 2003; Fleisig et al., 1995; Park et al., 2002a; Wilk et al., 2004), SWE is an excellent modality for understanding the changes going on in the tissues of the throwing arm in pitchers displaying the previously described injury risk factors. SWE has many benefits compared to more traditional methods of measuring tissue degradation, including first and foremost that it is non-invasive. Additionally it is cost-efficient, portable, and does not expose participants to radiation as opposed to radiography, MRI, or CT scans, or biopsy research.

Additionally, SWE can be used to record a full quantification of the material stiffness of throwing arm properties in as little as 15 minutes, in an athletic training room, just before a pitcher goes out to practice or a game. Chapter 2 of this report is the first research known to include the imaging of the UCL as well as several structures of the shoulder in a single, detailed, and comprehensive protocol for the use of SWE on structures of the throwing arm in adult men. While the results of the study show low reliability for the images of the change in UH joint space, it does show good reliability for the measurement of UCL material stiffness, which may be a more specific indicator of UCL health as opposed to the integrity of the medial elbow as a whole.

Knowing the material properties of interest and having a reliable methodology for the quantification of those properties allows for the scientific community to take large steps forward with future research. It is still unknown how these properties will present themselves in individuals with significant soft-tissue injures. There is some prior research that supports the belief that longitudinal monitoring of material stiffness of musculoskeletal structures may display drastic changes in stiffness immediately prior to the onset of significant soft-tissue injury (Salzano et al., 2015). Conducting longitudinal monitoring of the material stiffness of these tissues may allow for the detection of injury risk at a specific tissue level prior to the *"acute manifestation of chronic microdamage."* This would allow for a pitcher to perhaps miss a start or bullpen session, or even enter into several weeks of rehab, any of which are preferred to surgery and months on the disabled list. Performing research evaluating the inter-rater relatability of measuring changes during longitudinal tracking should be performed prior to any multi-site prospective injury research.

Additionally, standardizing or even automating the image processing portion of the imaging studies may provide increased reliability for ultrasound shearwave elastography imaging.

Once these steps have been completed, we must also identify specific kinematics and training programs that decrease the effect of pitching on the material properties that are related to injury risk. Once that research has been completed and those results analyzed, the field can work towards teaching and coaching safer pitching mechanics as well as designing individualized training and recovery protocols specifically designed to maintain and improve the health of the soft-tissue structures in the throwing arm. These next steps have the potential of dramatically decreasing the frequency and severity of injuries to the throwing arms of baseball pitchers.

This research is not without limitations and there are several that should be acknowledged. First, this research is cross-sectional in nature and it is unknown if any of the participants had serious elbow or shoulder injuries in the time following the data collections. We are also unable to account for the baseline values of material stiffness prior to any pitching, so any assumptions of change are based on using the non-throwing arm as a healthy baseline value. SWE imaging was also performed while the pitchers were in pre-season training mode as opposed to a true off-season, rested baseline. This was done to record soft-tissue property values as close to the recording of the range of motion and pitching biomechanics as possible. If the imaging had been conducted during an off-season imaging session, we would have expected larger bilateral differences in shoulder structures showing elevated tissue stiffness, which may have resulted in stronger relationships to pitching mechanics and range of motion values.

It is also of note that while all participants in this research were competitive baseball pitchers, some were starting pitchers and others were relievers which could lead to discrepancies in historical workload across the sample. All pitchers were not from the same organization and thus it is not appropriate to attribute any chronic changes to training effects of baseball specific drills or practice as the different pitchers would have different histories. Additionally, the pitchers used in this research were non-homogenous with regard to their exact level of competition or number of years competing at levels above high school. For example, a college freshman may display different property changes than a senior who has been training and competing at that level for a longer amount of time. Future research should be performed to understand the direction and magnitude of adaptations in the material properties of soft-tissues in young adult pitchers.

Conclusion

The research described in this document adds significant new research and understanding of the effect of baseball pitching on the critical soft-tissue structures of the throwing arm in adult baseball pitchers. At the conclusion of this research we know that pitchers with elevated shoulder kinetics during the pitching motion displayed decreased material stiffness of shoulder tendons. Additionally, pitchers with GIRD and TRM range of motion deficits were found to have significantly stiffer posterior shoulder structures than pitchers without GIRD or TRM deficits and a significant interaction was found between Arm and GIRD for supraspinatus tendon stiffness. This research suggests that using the non-throwing arm as a baseline measurement (if reflective of the native state of the throwing arm), material stiffness may be used to determine pitchers that are likely to present themselves with clinical injury risk factors. The findings from this research linking material property changes to injury risk factors provide biological evidence to strengthen the argument that soft-tissue injuries in baseball pitchers are a result of chronic microtrauma produced by repetitive exposure to extreme loads during the baseball pitching motion. This research outlines the methodology for quantifying this chronic microtrauma through the monitoring of tissue material properties, which can transform the way in which medical personnel approach and react to the health of a pitcher's throwing arm. Building off of the findings described in this dissertation and using the imaging protocol developed through this research, SWE can be used to measure the material properties of numerous critical structures, track tissue health, and ultimately lead to a reduction in the frequency and severity of soft-tissue injuries in baseball pitchers.

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APPENDIX A: IRB APPROVAL FOR AIM 1

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board
4N-64 Brody Medical Sciences Building· Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office **252-744-2914** · Fax **252-744-2284** · rede.ecu.edu/umcirb/

Notification of Amendment Approval

From: Biomedical IRB
To: Zachary Domire
CC:
Date: 1/28/2020
Re: Ame2_UMCIRB 19-002121
UMCIRB 19-002121
Relating Soft-Tissue Properties to Pitching Mechanics

Your Amendment has been reviewed and approved using expedited review on 1/27/2020. It was the determination of the UMCIRB Chairperson (or designee) that this revision does not impact the overall risk/benefit ratio of the study and is appropriate for the population and procedures proposed.

Please note that any further changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. The investigator must submit a Final Report application to the UMCIRB prior to the Expected End Date provided in the IRB application. If the study is not completed by this date, an Amendment will need to be submitted to extend the Expected End Date. The investigator must adhere to all reporting requirements for this study.

Approved consent documents with the IRB approval date stamped on the document should be used to consent participants (consent documents with the IRB approval date stamp are found under the Documents tab in the study workspace).

The approval includes the following items:

Document	Description
PitchingMechanics_TissueProperties_InformedConsent - 1-27-20.pdf(0.05)	Consent Forms
Adding Diamond Xtreme as a data collection site	

For research studies where a waiver of HIPAA Authorization has been approved, each of the waiver criteria in 45 CFR 164.512(i)(2)(ii) has been met. Additionally, the elements of PHI to be collected as described in items 1 and 2 of the Application for Waiver of Authorization have been determined to be the minimal necessary for the specified research.

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

APPENDIX B: IRB APPROVAL FOR AIMS 2 AND 3

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board
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Office **252-744-2914** · Fax **252-744-2284** · rede.ecu.edu/umcirb/

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The approval includes the following items:

Document	Description
PitchingMechanics_TissueProperties_InformedConsent - 1-27-20.pdf(0.05) Adding Diamond Xtreme as a data collection site	Consent Forms

For research studies where a waiver of HIPAA Authorization has been approved, each of the waiver criteria in 45 CFR 164.512(i)(2)(ii) has been met. Additionally, the elements of PHI to be collected as described in items 1 and 2 of the Application for Waiver of Authorization have been determined to be the minimal necessary for the specified research.

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

APPENDIX C: BILATERAL SOFT-TISSUE PROPERTIES OF THE ARM IN HEALTHY ADULT MALES: QUANTIFICATION USING SHEARWAVE ULTRASOUND ELASTOGRAPHY

Introduction

Ultrasonic imaging has emerged as a leading methodology for the visualization and quantification of musculoskeletal properties in athletic populations. Ultrasound's use has become widespread because it is relatively inexpensive compared to other imaging methodologies, more portable than other imaging methods, and does not have the concern of exposure to ionizing radiation (Bica et al., 2015; Yamauchi et al., 2016). Traditional ultrasound has provided tremendous insight into the structural properties of soft-tissue structures such as the length, thickness, cross-sectional area, or pennation angle. One such subset of athletes are overhead throwing athletes, who suffer soft-tissue injuries to their throwing arm at an alarming rate However, the failure of any of the structural changes reported in previous research to be a strong predictor of future injury indicates the need to expand research into new directions to determine indicators of elevated injury risk.

Recent research suggests investigating changes in the material properties of soft-tissue structures of the throwing arm is a promising new direction in the quest to identify elevated injury risk and reduce the occurrence of significant injuries in the throwing arms of overhead throwers, such as baseball pitchers (Yamauchi et al., 2016). One such new methodology is shearwave ultrasound elastography (SWE). Ultrasound elastography is the use of ultrasonic imaging to measure the degree of distortion of a specific tissue in response to an internal or external stimulus (Rosskopf et al., 2016). Specifically, SWE uses conventional ultrasound waves to interact with the tissue of interest and induce shear waves that are directed horizontally and propagate throughout the tissue. SWE then measures the velocity of the shear waves and uses those measurements in calculations to estimate tissue composition and elasticity (Drakonaki et al., 2012; Rosskopf et al., 2016). Ultimately, SWE estimates Young's modulus and produces material stiffness, *(Δstress / Δstrain)*, values in kPa. The product of SWE is an image referred as an elastogram, which includes a color-mapped image of the tissue of interest. The image is also able to be processed to view the quantitative stiffness values in addition to the color map.

Using SWE, bilateral differences in the material stiffness of the UCL in asymptomatic college-aged baseball pitchers, showing significantly lower material stiffness in the throwing arm than the non-throwing arm in during a pre-season research session (Curran et al., 2016). This difference suggests the presence of chronic damage experienced by the ligament during repetitive overhead throwing, resulting in increased medial joint laxity and the structural observation of increases in ulnohumeral joint gap. Additionally, the infraspinatus and teres minor of the throwing shoulder have demonstrated increased muscle stiffness due to chronic muscle damage compared to the non-throwing shoulder (Yamauchi et al., 2016). Preliminary evidence also suggests musculotendinous stiffness of the posterior rotator cuff as the primary mechanism for shoulder ROM deficits in baseball players (Bailey et al., 2015), again describing material property changes as the probable initial cause for the structural adaptations often reported in baseball pitchers. Traditional B-mode ultrasound research has identified bilateral differences in structural properties of the UCL including ligament length and thickness, ulnohumeral (UH) gap space and the change in UH gap space under valgus load (Atanda et al., 2015; Bica et al., 2015; Ciccotti et al., 2014; Nazarian et al., 2003).

These prior studies support our belief that a greater understanding of the changes in the material stiffness of the critical soft-tissue structures in the throwing arm is the key to understanding the underlying causes of overuse injuries in baseball pitchers. However, in order to understand the extent to which bilateral differences in soft-tissue properties are a result of the extreme loads experienced by the throwing arm during the overhead throwing motion, a normative amount of bilateral difference in healthy adult males must be established. **Thus, the objective of this research was to evaluate bilateral differences in the structural and material properties of soft-tissue structures in the arms of healthy adult males.**

Methods

A comprehensive imaging protocol was designed to quantify the structural and material properties of critical soft tissue structures in the throwing arm. 16 recreationally active men between the ages of 18 and 30 participated in bilateral ultrasound elastography imaging of their shoulders and elbows. Upon arriving to the Performance Optimization Lab, participants provided informed consent and had their height and weight measured. Prior to beginning the imaging protocol, participants completed a demographic and injury history questionnaire. Exclusion criteria for participation in this research included prior elbow or shoulder surgery on either arm, or a BMI ≥ 35. Participants were asked to refrain from significant upper body resistance training between imaging sessions. All participant demographics can be found in Table 14.

Table 14. Bilateral Imaging Participant Demographics

	Mean	**SD**
n	16	
Height (m)	1.80	0.06
Mass (kg)	86.19	10.25
Age at Collection (yrs)	21.46	1.77
Throwing Arm (L/R)	1 / 15	

We identified specific soft-tissue structures of interest prior to designing this protocol based on the most common soft-tissue injuries experienced by overhead throwing athletes. The structures are the ulnar collateral ligament (UCL), supraspinatus muscle and tendon, infraspinatus muscle and tendon, biceps brachii long head muscle and tendon. All imaging was performed by a single imager with 5 years of musculoskeletal ultrasound experience. All images and measurements were performed using a Supersonic Aixplorer Ultrasound system (Supersonic Imagine, Aix-en-Provence, France). The imaging protocol and data processing methodology used for this examination is described in detail in Chapter 1.

A sample of 20 generally healthy and recreationally active males was estimated to be sufficient to evaluate the reliability of the protocol based on prior musculoskeletal ultrasound imaging reliability studies using sample sizes between 15-25 participants (Bica et al., 2015; Rosskopf et al., 2016; Yamauchi et al., 2016). Bilateral differences were evaluated using a dependent sample t-test, with significant differences being defined as those relationships with a p value < 0.05.

Results

Mean and standard deviation values for each tissue of interest are found in Table 15. A significant bilateral difference was found for UCL length, showing that the UCL is longer in the throwing arm than the non-throwing arm (22.1 ± 1.2 mm vs 21.5 ± 1.5 mm, $p = 0.029$). No other significant bilateral differences were found for any structural or material property for the UCL, supraspinatus, infraspinatus, or biceps brachii long head muscles or tendons.

Table 15. Bilateral Differences in Arm Soft-Tissue Properties in Adult Males					
	Throwing		Non-Throwing		p-Value
	Mean	St. Dev	Mean	St. Dev	
UCL Stiffness (kPa)	216.5	35.5	217.6	39.5	0.896
UCL Length (mm)	22.1	1.2	21.5	1.5	**0.029***
UH Joint Space - Supported (mm)	4.1	0.0.5	4.0	0.6	0.569
UH Joint Space - Valgus (mm)	4.2	1.2	4.3	1.3	0.589
Delta UH Joint Space (mm)	0.4	0.2	0.6	0.3	0.177
Supraspinatus Muscle (kPa)	23.8	6.3	27.7	9.6	0.107
Supraspinatus Tendon (kPa)	167.1	32.4	173.3	26.7	0.388
Infraspinatus Muscle (kPa)	23.8	7.1	22.4	5.4	0.315
Infraspinatus Tendon (kPa)	167.5	26.9	158.9	36.0	0.275
BBLH Muscle (kPa)	35.3	9.8	36.7	8.6	0.427
BBLH Tendon (kPa)	79.3	25.7	85.6	33.1	0.225

Discussion and Conclusion

Our results demonstrate that there is no bilateral difference in material stiffness of the UCL, supraspinatus muscle and tendon, infraspinatus muscle and tendon, or biceps brachii long head muscle and tendon. Additionally, there was no significant bilateral difference in the UH joint space at rest or under a valgus load, nor in the delta UH joint space from rest to valgus loaded. These results suggest that any bilateral differences reported for any of these properties in baseball pitchers are likely due to the unilateral extreme loading experienced during the overhead throwing motion used in baseball pitching.

Our results do show that the UCL in the throwing arm is significantly longer than that in the non-throwing arm. This indicates that bilateral differences seen in UCL length of baseball pitchers may not solely be due to the stress of baseball pitching, and that UCL may not be the best indicator of baseball pitching injury risk.

APPENDIX D: CALCULATION OF UPPER BODY KINEMATICS AND KINETICS DURING BASEBALL PITCHING

Introduction

This appendix will provide details on the methods used to collect 3D motion data of the baseball pitching motion and calculate the kinematic and kinetic variables used in the analysis in Chapter 3, *Relationships between kinetic injury risk factors and the material stiffness of critical soft-tissue structures in the throwing arms of baseball pitchers.* It will provide additional detail regarding the data collection process, pre-processing in Qualysis Track Manager, calculations performed in Visual3D, and data analysis performed in MATLAB. All data for each pitcher was collected and processed using the methods described in this Appendix.

Data Collection

For the collection of 3D motion data, 52 passive motion capture reflective markers were placed on each pitcher's body. The marker set was based on those used in previous literature for the collection of upper body kinematics and kinetics during baseball pitching (Boddy et al., 2019; Hurd et al., 2011). A full body marker set was used to allow for the calculation of full body kinematics, as pitchers received a full-body biomechanical analysis of their pitching motion in return for their participation. Only the trunk and throwing arm was used for the calculations performed in Chapter 3.

The full body marker set used to collect motion data can be seen in Figure 17 The skin was marked with permanent marker prior to marker placement to allow for accurate replacement of any markers that may come off during data collection. Skeletal landmark markers were placed at the jugular notch, xiphoid process, C7, and T8 of the spine, as well as bilaterally on the acromion process, inferior angles of the scapula, medial and lateral epicondyles of the elbow, ulnar and radial styloids of the wrist, iliac crests, anterior and posterior superior iliac spines, medial and lateral femoral condyles, medial and lateral malleoli of the ankles, heels and the proximal 3rd phalanx of the feet. Skeletal landmark markers were placed at the 2nd and 5th metacarpophalangeal joints of the throwing hand, and at similar locations on the glove to identify the position of the non-throwing hand. Additional tracking markers were placed on the top, front, left, and right sides of the pitcher's hat, as well as bilaterally on the humerus, ulna, femur and tibia. Finally, tracking markers were place on the 1st and 5th distal metatarsal heads of the pitcher's back foot (ipsilateral to throwing arm).

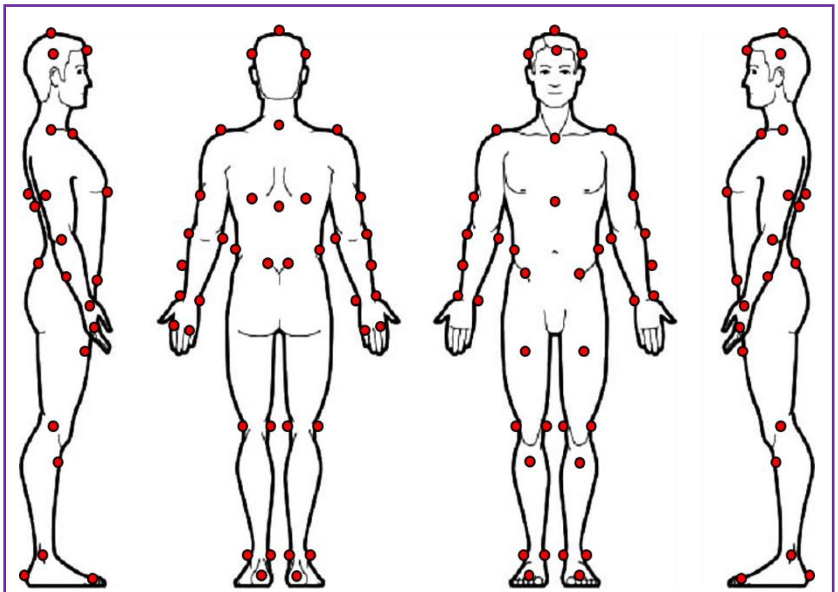

Figure 20. Bilateral full body marker set used for the collection of 3D motion data of the baseball pitching motion.

3D motion data was collected at 300 Hz using 12 Qualisys Oqus cameras (Qualisys AB, Göteborg, Sweden). The cameras were arranged at varying heights surrounding the pitching mound and were calibrated prior to each participant (Figure 18). Optimal camera placement was evaluated based on attempting several different iterations of alignment and height during pilot testing. Static calibration and half-speed pitching motion trials were collected and then pitchers instructed to perform their normal warm up routine as if they were preparing to pitch in a game. Pitchers were given as much time as necessary to stretch and warm-up, including pitching from the data collection mound, prior to pitching at full speed. After participants performed their warm-up and practice pitches from the mound, their first 10 fastball pitches were collected for this analysis.

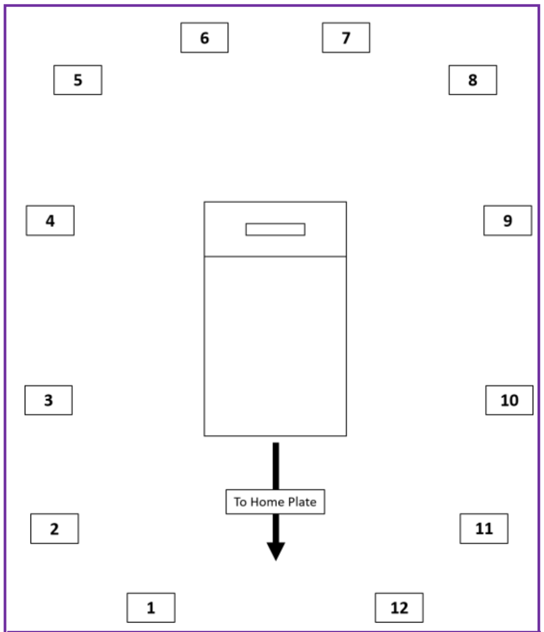

Figure 21. Camera set positioning for collection of pitching motion.

Marker trajectory pre-processing was performed in Qualisys Track Manager (QTM) (Qualisys AB, Göteborg, Sweden). Trials were trimmed to begin approximately 0.5 seconds prior to the pitcher's maximum knee height during the wind up and end approximately 0.5 seconds after the throwing arm had reached the end of the follow through phase. All trajectories were labeled and gap-filled, and any erroneous trajectories were removed. Files were then exported in .c3d format for data processing.

Data Processing

While a full body marker set was used to calculate kinematics for participants, the remainder of this appendix will focus on only the trunk and throwing arm kinematics and kinetics, as those were the only segments involved with the analysis in Chapter 3. All data was processed twice, once with the ball included in the model, and once without the ball included. This was done to have accurate kinematics before and after ball release, and the two sets of data were stitched together at a later point in the process.

Skeletal Model

Skeletal models were created for each pitcher in Visual3D (C-Motion Inc., Germantown, MD, USA) using the static calibration motion capture trial. Participants stood with their feet shoulder width apart, arms abducted 90°, and palms facing anteriorly. A representative static calibration trial and skeletal model constructed from it can be seen in Figure 19.

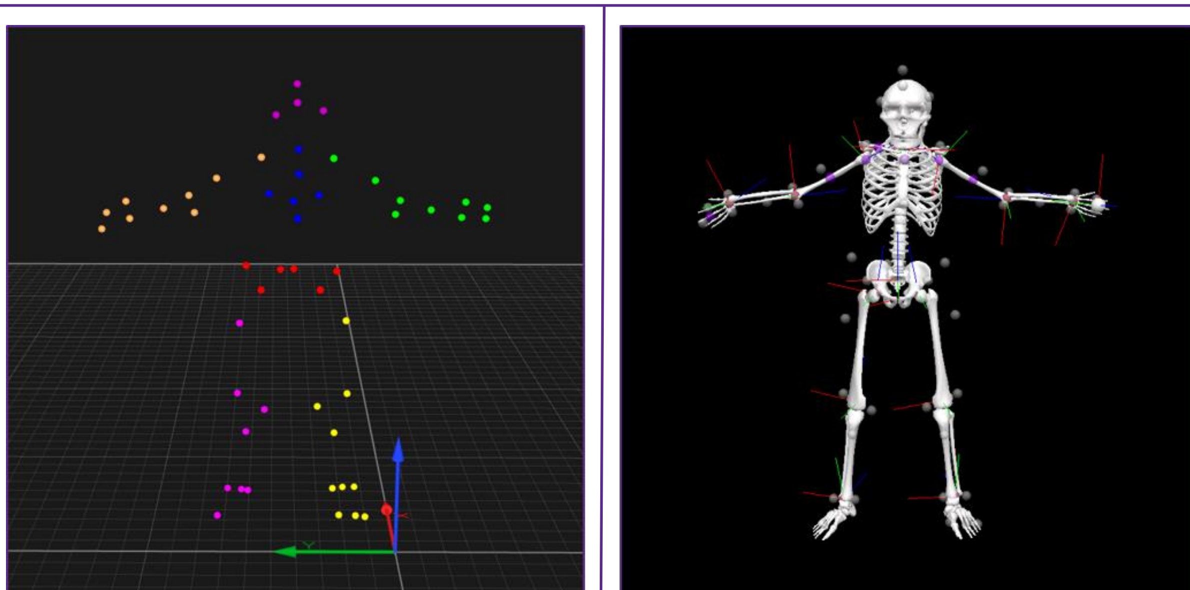

Figure 22. Pre-processed static calibration pose in Qualisys Track Manager and skeleton created from it in Visual3D.

Three virtual landmarks were created for the eventual identification of the thorax as suggested in the C-Motion documentation, in accordance with ISB recommendations ('Tutorial: Modeling the Thorax', 2015; Wu et al., 2005). A landmark for the upper thorax was created at the midpoint between the jugular notch and C7, and a landmark for the lower thorax was created at the midpoint between the xiphoid process and T8. A third thorax landmark was created as a lateral object for the thorax. This landmark was created halfway between the jugular notch and C7 markers, and 0.1 m off-center from the midline of the body, with the mid lower thorax marker identifying the lateral direction. Virtual joint center landmarks were created for the shoulder, elbow, and wrist of the throwing arm The landmark for the joint center of the throwing shoulder was offset from the throwing side acromion marker, moving down the longitudinal axis of the trunk by the radius of a marker plus 0.17*distance between acromions (Petuskey et al., 2007). The virtual landmark for the throwing arm elbow joint was created at the midpoint between the medial and lateral epicondyle markers of the elbow on the throwing arm. The wrist joint center landmark was created at the midpoint between the markers at the ulnar styloid and radial styloid. Three additional virtual landmarks were created for use with accurate calculation of kinetics and kinematics of the throwing motion. A virtual landmark for the midpoint of the throwing upper arm was created at the midpoint between the throwing arm shoulder joint and the throwing arm elbow joint. A virtual landmark for the center of the hand was created at 0.3*distance between the 2nd metacarophanlangeal marker and the wrist joint center, plus the marker radius. The hand center landmark was further defined by identifying the lateral wrist marker as a lateral object from the hand center. Lastly a virtual landmark was created at the interaction point between the ball and the hand, at the midpoint between the 2nd and 5th metacarpophalangeal markers and positioned on the anterior surface of the hand.

The thorax was defined using the upper and lower thorax landmarks and the third thorax landmark in accordance with the C-Motion documentation. The throwing arm shoulder joint center was used to define the proximal end of the upper arm and the distal end was defined by the markers on the medial and lateral epicondyles of the humerus. The proximal end of the throwing forearm was defined using the markers on the medial and lateral epicondyles of the humerus and the distal end of the forearm was defined by the markers on the styloids of the ulna and radius. The hand of the throwing arm was defined using the wrist joint center and hand center landmarks as well as the lateral wrist marker. Finally, the baseball was modeled as a 142-gram point mass with the mass applied to the hand in between the 2nd and 5th distal metacarpal heads (Boddy et al., 2019; Hurd et al., 2011; Hurd and Kaufman, 2012).

The skeletal model then had a top-down inverse kinematic linkage applied to it. For the data to be processed with the ball included in the skeletal model, the ball was used as the first segment in the IK linkage, with the LAB as its parent, connecting the entirety of the linkage to the global coordinate system during created during system calibration. The linkage then continued up the throwing arm, from the ball to the hand, followed by the forearm, upper arm, and finally the thorax. For the data to be processed without the ball in the skeletal model, the hand was the first segment in the linkage, followed by the forearm, upper arm, and finishing with the thorax.

Kinematics and Kinetics

All marker and landmark trajectories were processed using a low-pass butterworth filter with a frequency cutoff of 20 Hz, prior to the calculation of any kinetics or kinematics (Boddy et al., 2019). Joint angles and angular velocities were calculated for the thorax, shoulder, and elbow. Kinetic variables calculated included shoulder force and torque and elbow torque. Shoulder rotation was calculated using a Z-Y-Z cardan sequence to avoid a mathematical singularity when measuring shoulder internal and external rotation. All kinematics and kinetics were calculated in accordance with ISB’s recommendations for upper body joint coordinate systems (Wu et al., 2005).

Shoulder internal and external rotation were specific kinematic variables of interest. Shoulder internal and external rotation was calculated as rotation of the upper arm around the longitudinal axis of the upper arm, in reference to the thorax. Positive values indicate external rotation, and negative values indicate internal rotation. Shoulder internal and external rotation torque, shoulder compression and distraction force, and elbow valgus torque were kinetic variables of interest. Shoulder internal and external rotation torque were calculated as the joint torque of the upper arm around the longitudinal axis of the upper arm. Positive values indicated an external rotation torque and negative values indicated an internal rotation torque. Shoulder compression and distraction force was calculated as the joint force along the longitudinal axis of the upper arm. Positive values indicate a compressive force of the shoulder joint in response to an external distractive force, and negative values indicate a shoulder distraction force. Elbow varus and valgus torque was calculated as the joint torque of the forearm around the longitudinal axis of the upper arm. The values were multiplied by a negative one for visualization purposes so that positive values indicate an elbow varus torque in response to an external valgus torque.\

Events in the Pitching Motion

Kinematic and kinetic values and metrics were calculated using a series of events throughout the pitching motion: 1) Maximum Knee Height, 2) Maximum Shoulder External Rotation, 3) Front foot Contact, 4) Ball Release, 5) Maximum Shoulder Internal Rotation, and 6) End of Follow Through. Maximum knee height was defined as the instant that the proximal end of the stride leg (contralateral to the throwing arm) reached its highest point. Maximum external shoulder rotation was defined as the maximum shoulder rotation value. Foot contact was restrained so that it had to occur in between the stride ankle joint center crossing a vertical threshold of 5 centimeters, and the maximum shoulder external rotation event. Front foot contact was defined as the peak vertical descending velocity of the 3rd phalanx marker on the stride leg. Ball release was restrained to occur after maximum external rotation and was identified as 2 frames after the wrist joint center moved past the elbow joint center towards home plate. Maximum shoulder internal rotation was identified as the minimum shoulder rotation value in between maximum shoulder external rotation and the end of the follow through. Finally, the end of the follow through was identified as the instant after ball release that the throwing hand center of gravity was the furthest away from the batter.

Specific Kinetic Metrics of Interest

The two processed copies of the data (one with and one without the ball included in the kinetic chain) were then stitched together in Matlab to form a single set of data that would not include the ball after ball release. The set of data that included the ball in the kinetic chain was trimmed at the frame of ball release. The data without the ball was then appended to the existing data beginning at the frame after ball release until the end of the trial. All metrics and analyses were performed using this stitched data.

Seven specific kinetic variables were calculated for the analysis in Chapter 3. Peak shoulder compressive force was calculated as the absolute maximum value of the stitched shoulder compression and distractive force data. Mean shoulder compressive force was calculated as the mean value of the stitched shoulder compression and distraction force data between the events of front foot contact and ball release. Mean shoulder compressive force post-release was calculated as the mean value of the stitched shoulder compression and distraction force data between the events of ball release and the end of the follow through. Peak shoulder external rotation torque was calculated as the absolute maximum value of the stitched shoulder rotation torque data. Mean shoulder external rotation torque was calculated as the mean value of the stitched shoulder rotation torque data between the events of front foot contact and ball release. Peak elbow external valgus torque was calculated as the absolute maximum value of the stitched elbow valgus/varus torque data. Mean elbow external valgus torque was calculated as the mean value of the stitched elbow valgus/varus torque data between the events of front foot contact and ball release.

Sample Kinematic and Kinetic Graphs

Figures 20-24 are representative graphs for elbow flexion and elbow varus/valgus torque, shoulder compression / distraction force, and shoulder external rotation and external rotation torque for one participant. These graphs are visually and spatially similar to those in previously published literature (Fleisig et al., 1995; Kaizu et al., 2018; Werner et al., 1993). Examining the shoulder compression / distraction force graph near ball release, the effect of the pitcher releasing the ball can also be seen, indicating that the stitching of the ball/no ball data worked properly. Table 16 shows the mean values for each of the outcome variables calculated using this data processing method. These values are within the ranges of normative reports of these same variables in baseball pitchers. (Dillman et al., 1993; Fleisig et al., 1995; Fortenbaugh et al., 2009; Kaizu et al., 2018; Werner et al., 2007, 1999, 1993).

Table 16. Throwing Mechanics Mean Values

	Mean ± SD
Max Shoulder Compressive Force (N)	1009.27 ± 245.16
Mean Shoulder Compressive Force (N)	457.15 ± 114.80
Mean Shoulder Compressive Force Post Release (N)	424.14 ± 119.34
Max Shoulder External Rotational Torque (Nm)	90.28 ± 20.67
Mean Shoulder External Rotation Torque (Nm)	55.18 ± 12.57
Max Elbow External Valgus Torque (Nm)	85.12 ± 19.65
Mean Elbow External Valgus Torque (Nm)	51.98 ± 11.98

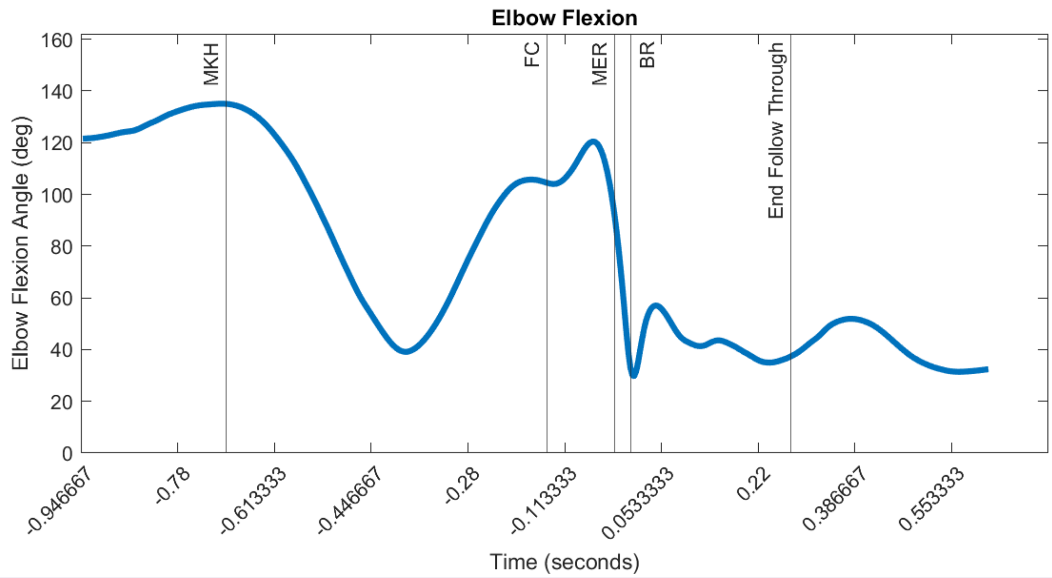

Figure 23. Elbow flexion during the baseball pitching motion. Key timepoints shown include maximum knee height (MKH), front foot contact (FC), maximum shoulder external rotation (MER), and ball release (BR).

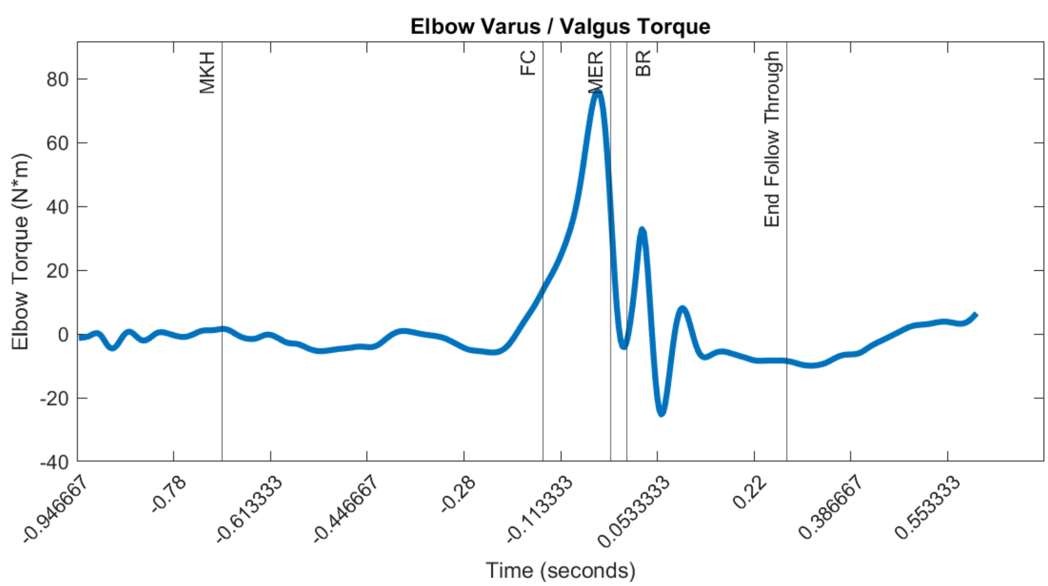

Figure 24. Elbow varus / valgus torque during the baseball pitching motion. Key timepoints shown include maximum knee height (MKH), front foot contact (FC), maximum shoulder external rotation (MER), and ball release (BR).

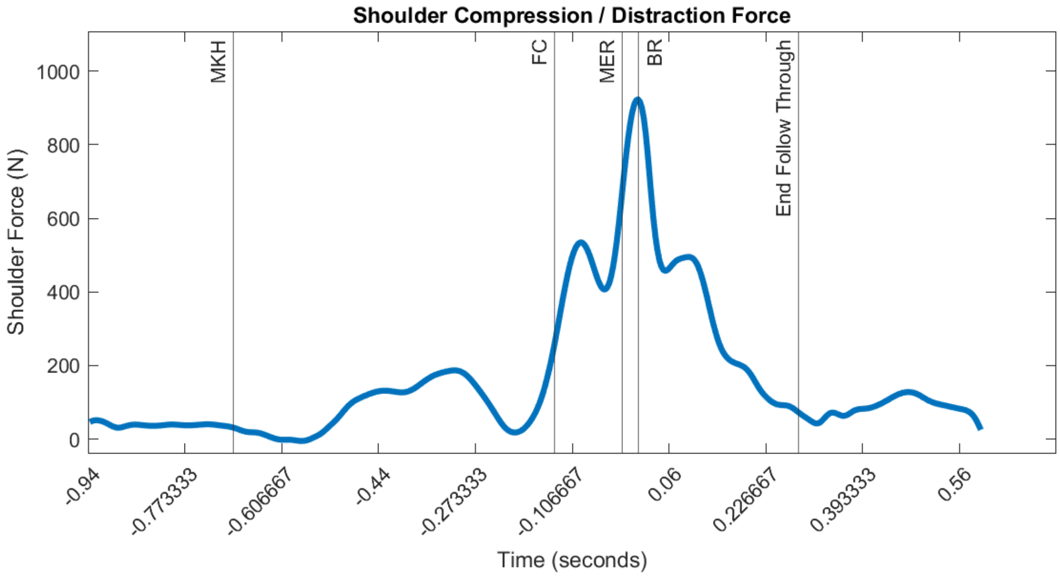

Figure 25. Shoulder compression / distraction force during the baseball pitching motion. Key timepoints shown include maximum knee height (MKH), front foot contact (FC), maximum shoulder external rotation (MER), and ball release (BR).

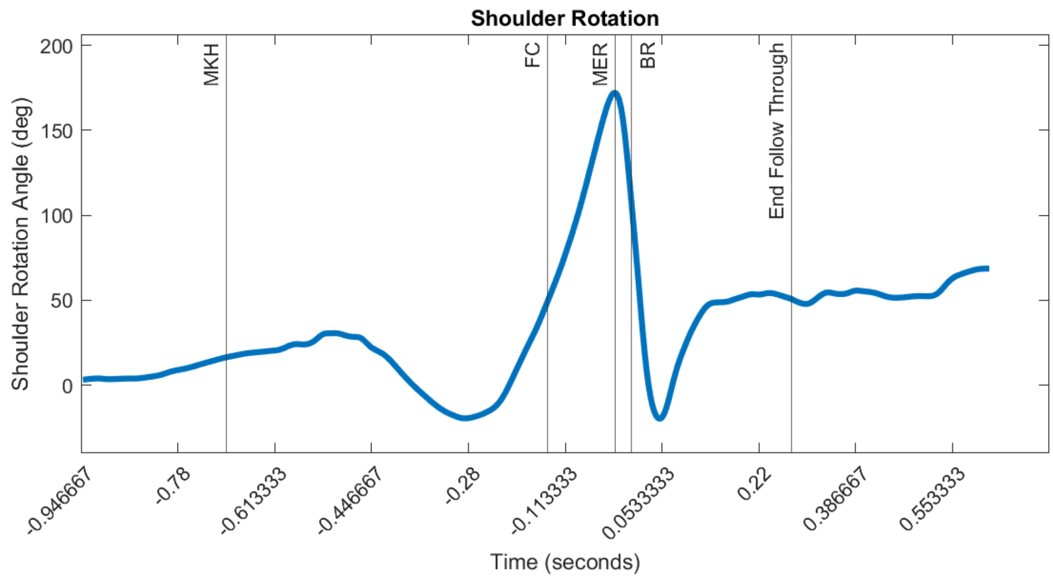

Figure 26. Shoulder internal / external rotation during the baseball pitching motion. Key timepoints shown include maximum knee height (MKH), front foot contact (FC), maximum shoulder external rotation (MER), and ball release (BR).

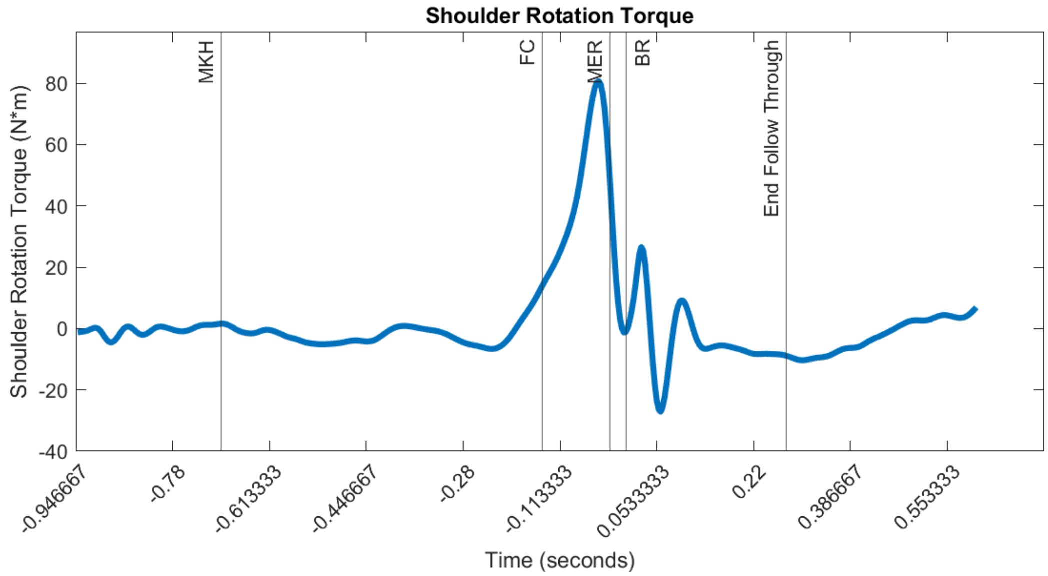

Figure 27. Shoulder internal / external rotation torque during the baseball pitching motion. Key timepoints shown include maximum knee height (MKH), front foot contact (FC), maximum shoulder external rotation (MER), and ball release (BR).