
SHEARWAVE ELASTOGRAPHY: A PROSPECTIVE STUDY ON SHORT TERM CHANGES IN UCL
HEALTH OF COLLEGE BASEBALL PITCHERS

by

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The rate of ulnar collateral ligament (UCL) reconstruction surgery, or “Tommy John” surgery, has risen dramatically in baseball pitchers over the last decade. Throughout the baseball pitching motion, the UCL undergoes tremendous tensile stress, placing it at increased risk of injury in overhand throwing athletes. Because of these demands placed on the medial elbow, morphological adaptations have been shown to occur in the throwing arm of baseball pitchers such as increased UCL cross-sectional area and increased joint laxity. It is currently unknown if the material properties of the tissue are changing as well.

Ultrasound shearwave elastography (SWE) is a relatively new tool for the quantitative evaluation of the material properties of connective tissue in vivo. It has been recently used to assess differences in ligament stiffness in patients exhibiting symptoms of frozen shoulder, as well as Achilles tendon stiffness while recovering from surgery. The hypothesis of this thesis is that UCL stiffness increases after a pitching bout and returns to baseline throughout the following days. The purpose of this study is to observe the material properties of the UCL after a pitching bout and evaluate change in stiffness compared to baseline.

6 collegiate baseball pitchers between the ages 18-25 participated in this study. SWE measurements were collected the day prior (Baseline), and the 4 days following the pitching bout (Days 1-4). Ulnohumeral joint space was measured in both supported and stressed conditions, the difference between the two representing joint laxity. Participants also completed the Kerlan-Jobe Orthopedic Clinic Overhead Athlete questionnaire as a measure of self-reported arm health.

No significant changes in stiffness were observed within the study timeframe. Mean stiffness increased by 30.7kPa (12.8% of Baseline) after the pitching bout (Day 1), and 5 of the 6 participants experienced an increase in stiffness. One participant exhibited a severe drop in stiffness (63.4kPa; 29.5% of baseline), who also reported the lowest cumulative KJOC score of the participant pool (indicating increased risk of injury). The removal of this outlier increases the effect size of the change in stiffness between Day 1 and Day 4 from small (ES = 0.37) to moderate (ES = 0.56). No significant changes in the joint space were observed.

This prospective study suggests ultrasound SWE may have practical application as a biomarker of UCL health. The direction of the change in UCL stiffness may be related to the current health status of the tissue. Limitations included a small sample size, varying pitch counts and types among participants, and a wide range of pitcher skill level and arm health. Although more research is needed, this thesis provides insight into the material property changes of the ligament during the 4 days following pitching.

Shearwave elastography: A prospective study on short term changes in UCL health of college
baseball pitchers

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INTRODUCTION

UCL tears are an increasingly common injury in MLB pitchers despite advances in modern medicine. As of May 2015, at least 113 MLB pitchers underwent Tommy John’s surgery since 2010. Only 101 pitchers had the surgery from 2001 to 2009⁴². Not only does this surgery have the inherent risk of any medical procedure, it costs the player valuable time during recovery. Clearly, this is a problem in the professional level, but the roots of the injury stem from long before professional careers begin. In 2001, the American Academy of Pediatrics estimated over 4.5 million adolescents between the ages of 5 and 14 years old play baseball in the United States. It has been reported that approximately 17% of these participants reported elbow discomfort, with other studies showing an incidence of up to 20%^{36,28}. The prevalence of elbow pain is accompanied by a growing trend of UCL surgeries in youth baseball players. In 1994, Dr. James Andrews and Dr. Glenn Fleisig performed two UCL reconstruction surgeries on youth players all year, accounting for 10% of all Tommy John surgeries performed in their practice (Table 1). By year 2008, youth surgeries represented 31% of the Tommy John surgeries they performed (28 UCL reconstructions) that year²⁰.

TABLE 1
Ulnar collateral ligament reconstructions
for baseball pitchers at Andrews Sports
Medicine²⁰

Year	Youth and High School	Total	% Youth and High School
1994	0	6	0%
1995	2	21	10%
1996	1	31	3%
1997	1	23	4%
1998	5	43	12%
1999	12	65	18%
2000	17	93	18%
2001	17	93	18%
2002	19	110	17%
2003	45	172	26%
2004	35	174	20%
2005	42	153	27%
2006	36	140	26%
2007	38	125	30%
2008	28	89	31%
TOTAL	298	1338	22%

The anterior bundle of the UCL is the primary restraint to valgus stress at the elbow between 20° and 120° of flexion⁴⁵⁻⁴⁷. This duty of the UCL is of great relevance to the overhand throwing athlete, as repetitive throwing motions place the athlete at increased risk for injury¹⁰. The pitch is traditionally comprised of six different phases^{20,63}. It consists of the windup, followed by the stride, arm cocking phase, acceleration phase, deceleration phase, and follow-through. Of particular importance with regard to UCL injury are the arm cocking and acceleration phases. These phases represent the change in direction of the baseball as the pitcher converts the elastic energy stored in the internal rotators of the shoulder joint and elbow extensors to forward momentum in the acceleration phase^{10,59}. During this phase, the elbow undergoes tremendous valgus stress that can lead to injury of the UCL^{10,20,59}.

The medial elbow undergoes a number of adaptations throughout a baseball pitcher's playing career, including increased cross-sectional area (CSA) of the UCL, increased ulnohumeral joint laxity, as well as increased hypoechoic foci and calcifications^{11,48,59}. Although these adaptations have been observed in asymptomatic pitchers, they may be more prevalent in pitchers experiencing elbow pain⁵⁹. Ligament CSA thickening is a known indication of the ligament healing process²⁵, which leads us to believe this adaptation may be a sign of accumulated damage, rather than a protective mechanism. The standard rest protocol for starting pitchers in professional baseball is usually 4 to 5 days before pitching another game. With the rate at which Tommy John's surgery is increasing, it may be time to reevaluate the necessary days off between games started, and to explore the possibility that team managers may be sending pitchers back to the diamond too soon. The development of shearwave elastography may offer valuable insight to the elbow health of these players.

Shear wave elastography has been shown to have the ability to detect short term (< 2 weeks) changes in ligament stiffness in horses^{38,39}. It has also been shown to quantify differences in coracohumeral ligament stiffness between patients with adhesive capsulitis, and healthy participants⁶⁴. Due to the microtrauma experienced by the UCL during a baseball pitch, SWE may be able to identify changes in stiffness of the UCL before and after a pitching bout. It is the purpose of the current study to build off these two studies and determine if shear wave elastography can be used to measure short term changes in mechanical properties of the UCL, if changes in the UCL are indeed occurring. The current study proposes the use of the shear wave elastography as a method to quantify the short-term changes in tissue stiffness as an indicator of health of the UCL in college baseball pitchers.

Hypothesis

We expect to see an increase in ligament stiffness following game-intensity pitching bouts in relation to baseline ligament stiffness, in college baseball pitchers.

Purpose

The purpose of this study is to measure acute changes in the material properties of the UCL in college baseball pitchers following the repeated, high magnitude strains experienced during a pitching bout.

Significance

This study is the first to examine the short-term changes in material properties of the UCL using shear wave elastography. Previous studies have observed morphological adaptations to the UCL over a player's career, although this information leaves us to speculate the changes of the material properties in vivo. In addition, little research exists utilizing shear wave elastography to assess ligament stiffness, as much of the recent focus on musculoskeletal application has been directed to muscle and tendon.

Delimitations

- 1) All participants will be males on the ECU club baseball team.
- 2) Participants will be between 18-25 years old.
- 3) This study will only be examining pitching bouts of at least 50 pitches.
- 4) Pitchers must be healthy, with no prior history of surgical intervention on the dominant elbow.
- 5) Acute injuries of the medial elbow during the observed pitching bout will invalidate the trial. This study is focusing on material changes that occur after a standard pitching bout, not one in which the pitcher sustains injury.

Limitations

- 1) Stiffness readings and calculations are restricted to the accuracy of the ultrasound system.

-
- 2) Readings will not be made on the day of the observed pitching bout due to logistical purposes. Additionally, it is unknown how increased blood flow, swelling, and muscle tension exhibited post-exercise affect stiffness readings using SWE.
 - 3) Exact number of pitches thrown, as well as types of pitches thrown will vary between participants. This may lead to inconsistencies in change of UCL material properties among participants.

Assumptions

- 1) We assume the UCL is under sufficient tension during elastography readings to remove collagen crimp, ensuring the stiffness readings represent the Young's Modulus in the linear region of the stress-strain curve.
- 2) The pitcher is well rested and does not have a significant amount of accumulated fatigue prior to the observed throwing session.

REVIEW OF LITERATURE

Introduction

The purpose of the current study is to determine if ultrasound shear wave elastography is an effective method for measuring short term changes in health of the UCL of college baseball pitchers. The following literature review will discuss: 1) UCL injury in baseball pitchers 2) responsibilities of the UCL during pitching 3) ligament composition and injuries, 4) changes in the ulnar collateral ligament in baseball pitchers, and 5) the potential of ultrasound elastography in ligament pathology diagnosis.

UCL Injury in Baseball Pitchers

UCL tears are an increasingly common injury in MLB pitchers despite advances in modern medicine. As of May 2015, at least 113 MLB pitchers went under the knife since 2010 (approx. 20 per year). Only 101 pitchers had the surgery from 2001 to 2009⁴² (approx. 11 per year). Not only does this surgery have the inherent risk of any medical procedure, it costs the player valuable months in recovery time. In a study with 179 MLB pitchers who underwent UCL reconstruction, the average return to the MLB took 20 months with a standard deviation of 10 months¹⁷. This is a significant portion of their career and in order to make this decision, the player must be confident about their likelihood of returning to high performance after the operation. However, the reality is, many players struggle to return to prior form. There is always some risk in any surgery, and Tommy John's surgery is no different. In 2014, Makhni et al.⁴¹ performed a study with 147 pitchers who underwent UCL reconstruction found that only

80% were able to return to pitching in the MLB post operation. They also found that over multiple categories, performance declined when comparing pre-injury levels to post operation levels. These metrics included increased earned run average, batting average against, walks plus hits per inning pitched, decreases in percentage of pitches thrown in the strike zone, innings pitched, percentage fastballs thrown, and average fastball velocity. Typically, professional and collegiate baseball pitchers are allotted 4 days for recovery between starting pitching bouts. This seems to be an adequate amount of recovery time anecdotally, however the rising rates of UCL injury may suggest otherwise.

Clearly, this is a problem in the professional level, but the roots of the injury stem from long before professional careers begin. In 2001, the American Academy of Pediatrics estimated over 4.5 million adolescents between the ages of 5 and 14 years old play baseball in the United States. It has been reported that approximately 17% of these participants reported elbow discomfort, with other studies showing an incidence of up to 20%^{28,36}. Factors related to elbow pain include year-round play, pitching in leagues without pitch counts, pitching for multiple teams, pitching and catching in the same game, and continued pitching despite elbow pain/fatigue^{19,40,41}. Those individuals pitching more than eight months per year had a 500% increased likelihood for later surgery^{8,16}. In 1994, Dr. James Andrews and Dr. Glenn Fleisig performed two UCL reconstruction surgeries on youth players all year, accounting for 10% of all Tommy John surgeries performed in their practice. By year 2008, youth surgeries represented 31% of the Tommy John surgeries they performed (28 UCL reconstructions) that year²⁰. The sheer number of pitches seems to be a major factor in elbow injuries, which is not surprising considering the demands placed on the UCL during the pitching motion.

Responsibilities of the UCL in Pitching

Ligament injury is commonly seen in clinical practice, yet our understanding of the changes in mechanical properties during injury recovery is incomplete⁵⁶. Ligaments are relied on by the musculoskeletal system to hold bony structures together allowing muscles to transmit force across joints. As they are the primary 'glue' of the skeletal system, they are critically important to body movement. During the baseball pitching motion, the UCL transmits forces of up to 34Nm across the elbow joint as the professional pitcher propels the ball forward²⁰. However, not all ligaments have this function. Ligaments are present in every joint in the body and due to this, ligament size, shape and orientation vary dramatically²³. In addition to holding bones together at articulating surfaces, they are responsible for maintaining joint congruency and guiding joint motion while preventing unwanted movement which would result in instability²⁴. The elbow joint for example, works in one plane of motion, the sagittal plane. Being a hinge joint, it's only types of motion are flexion and extension. The ulnar collateral ligament and radial collateral ligaments together prevent valgus and varus dislocation of the humerus and forearm respectively and allow effective transmission of force across the elbow joint.

Ligaments may also assist in proprioception, sending information regarding joint angle and tensile stress to the brain via afferent motor pathways²⁴. In 1991, Johansson et al.³² found evidence that ligaments may function as a neurological feedback loop. This constant feedback loop could prove useful in providing vital orientation information to the premotor cortex during highly coordinated movements such as jumping or changing direction. These findings were concurred by Michelson et al.⁴³ in 1995. They examined the ligaments from five cadavers and

found mechanoreceptors that correlated with the four types of mechanoreceptors previously reported in cats by Freeman and Wyke²⁶ in 1967. However, this is still a disputed role of ligaments due to conflicting findings. In 1994, Feuerbach et al.¹⁸ tested twelve uninjured subjects to match prior ankle positions after the application of a local anesthetic applied to the anterior talofibular and calcaneofibular ligaments. No significant differences were found between the control and experimental trials leading them to conclude that ligament mechanoreceptors contributed negligibly to ankle joint proprioception. These findings appear to suggest that although there are clearly mechanoreceptors in ligamentous tissue⁴³, they probably play a minor role in joint proprioception, while muscles and tendons play a more significant part in detecting joint angle.

In 1991, Johansson et al.³¹ explored how ligament tension affects the surrounding musculature. He found that even relatively moderate tension of the cruciate ligaments of the knee elucidated changes in muscle spindle afferent activity, and that this could possibly lead to the stiffening of the surrounding musculature in the knee joint. This stiffening of the surrounding musculature almost certainly happens during the pitch, as the cumulative force that is placed on the medial elbow far surpasses the tensile strength of the UCL alone⁴⁵. This is also something to be considered while performing stiffness measurements of study participants with valgus stress applied to the elbow. Muscle guarding has been shown to be elicited by ligament tension, something we are purposefully inducing during stiffness measurements to ensure readings are taken from the linear region of the stress-strain curve.

The anterior bundle of the UCL is the primary restraint to valgus stress at the elbow between 20° and 120° of flexion^{27,45-47}. In 1991, Morrey et al.⁴⁶ demonstrated this by

sequentially removing structures that constrain valgus stresses at the elbow joint, and quantifying the loss in stability after each structure was removed. The radial head and posterior bundle of the UCL are contributors in the resistance of valgus force, however the greatest changes in abduction displacement were observed with the removal of the anterior band of the UCL. This responsibility places the anterior band at the highest risk for injury, as it is the most commonly injured portion of the ligament²⁷. Although this band is the primary static restraint to valgus stress, the posterior band of the UCL is frequently injured concurrently in UCL tears. The elbow stabilization required of the UCL is of great relevance to the overhand throwing athlete, as the repetitive throwing motions place the athlete at increased risk for injury¹⁰.

The pitch is traditionally comprised of six different phases^{21,63}. The pitch is initiated with the windup, followed by the stride, arm cocking, acceleration phase, deceleration phase, and follow-through. Of particular importance with regard to UCL injury are the arm cocking and acceleration phases. These phases represent the change in direction of the baseball as the pitcher converts the elastic energy stored in the internal rotators of the shoulder joint and elbow extensors to forward momentum in the acceleration phase^{10,59}. In a study of 26 competitive baseball pitchers, Fleisig et al. showed peak elbow varus torque to reach 64 ± 12 Nm shortly before the shoulder reaches maximal external rotation, with the elbow flexed at $95 \pm 14^\circ$ ²⁰. In a previous study, Morrey et al. found that at 90° of flexion, the UCL was responsible for 54% of varus torque at the elbow⁴⁵. Using Morrey's findings, the UCL produced 34.6 Nm of torque to resist the valgus stresses induced by the pitching motion. Prior work has shown cadaveric UCL tensile strength to only reach 34.29 ± 6.9 Nm prior to failure¹, however factors such as muscle contraction likely compensate for this difference. During a pitch, the load on the

UCL appears to approach its failure point, which is thought to play a major role in the development of ligament pathology.

Ligament Composition

Ligaments are relatively inert structures, composed primarily of water and collagen with relatively few metabolically active cells called fibroblasts⁶. This structural composition allows ligaments to withstand great tensile forces which the tissue is likely to experience during function. Fibroblasts are heterogeneous in nature, varying in shape, size, orientation, and number. Generally, they are spindle shaped, and oriented longitudinally along the long axis of the ligament, however they probably do not assist in resisting tensile loads directly. Instead, they help indirectly by maintaining the structural integrity of the ECM (extra cellular matrix). This is accomplished by measuring the amount of deformation that occurs with a given force, which informs the cell of the material properties of the surrounding tissue⁵⁴. Duties of the fibroblast consist of synthesizing new extra cellular matrix in response to damage or maturation²⁹, as well as the degradation of old or injured ligament tissue⁶¹. The bulk of ligament function is carried out by the ECM, while fibroblasts work to maintain the structural integrity of the ligament. This constant remodeling of collagen fibers is crucial to the health of heavily loaded ligaments, like that of the UCL in baseball players. Due to the microtrauma experienced by the medial elbow during pitching bouts, 4 days of rest are given so that the UCL (among other tissues) has time to repair any damaged collagen fibers, allowing the joint to function properly.

The ECM is a combination of collagen, elastin, proteoglycans and water. Collagen is a dense, fibrous protein that makes up the extracellular matrix within ligaments as well as many other types of connective tissue such as tendon, bone, and skin. In ligaments, it accounts for 70-80% of the tissue's dry weight³. The most common type of collagen found in ligaments is type I, however smaller quantities of types III, V, and VI are also present⁶⁰. Collagen is extremely strong due to the molecular cross-links it can create with adjacent collagen fibers. Elastin is found in ligaments to a small degree (1.5%), and is thought to contribute to the tissue's tensile resistance, as well as ligament's ability to regain original length after strain. It also may help to protect collagen by helping share the load, at least at low strains. Proteoglycans account for less than 1% of the dry weight of ligament. While this may seem rather insignificant, it's strong hydrophilic propensity plays a vital role in its effect on water content and the ligament's viscoelastic properties. These components of the ligament are large factors in its material properties such as stiffness and extensibility. If changes in stiffness are seen in the UCL after a pitching bout, it likely is due to one of these factors.

Ligaments have a nonlinear force-deformation curve. This change in stiffness relative to percent strain is thought to allow joint movement under low loads, while still being able to protect itself as the tensile force is increased. As the tensile force experienced by the ligament increases, stiffness rises as well. The non-linear force-deformation curve is explained by two structural details. Collagen is usually thought of as a strong, straight band making up the midsubstance of the ligament, however it is only straight when under strain. When relaxed, it has a curvy undulating pattern. This wavy pattern produces slack when a ligament is not resisting tensile force and is pulled taut when tensile forces increase. This wavy "slack" is known

as crimp. The second reason for ligaments non-linearity is the heterogeneous distribution of collagen fibers along the length of the ligament body. This entails that not all collagen fibers are recruited simultaneously at the start of force-bearing. Additionally, although most collagen fibers in the midsubstance run longitudinally, there are few smaller, weaker non-axial fibers which undoubtedly play a small role in the overall behavior of the ligament under strain. Now we will see how these two factors play into the force-deformation curve of ligaments.

The typical force-deformation curve for ligaments begins with a very flat slope. This region of the curve is called the toe region. This initial ease of deformation is thought to be caused by the flattening of collagen crimp. Once the crimp has been drawn tight, stiffness increases, and the slope of the curve begins to rise, which would typically occur during the arm cocking phase of the pitch. This increase in stiffness is observed until all the collagen fibers within the ligament body are loaded under tension. With all, or nearly all collagen fibers recruited, the ligament enters the linear region of the force-deformation curve. At this point, the curve takes on a linear path. Presumably, the point of the curve with the highest slope would be in the center of the linear region and is the point at which maximal fiber recruitment occurs. After this peak in slope, the force begins to drop off. This marks the end of the linear region and the beginning of the microfailure region. This region is characterized by the first collagen fibers failing to withstand their tensile load, most likely the first collagen fibers to be recruited in the toe region. When this occurs, the force that the failed collagen fiber was resisting, is now redistributed among the remaining collagen fibers of the ligament. It is easy to see how small microfailures can quickly compromise the integrity of the entire structure. The

acceleration phase of the pitch likely reaches this region of microfailure, which is why pitchers experience aches and soreness after a pitching bout¹⁰.

Gross failure of the ligament body is seen in the failure region, as the slope of the force-deformation curve quickly drops off and force returns to zero. Ligament strains of around 8% have been associated with this level of failure in the rabbit MCL³⁵. Acute ligament ruptures usually result from tensile forces exceeding the strength of the ligament. In the case of the baseball pitcher, the tensile stress the medial elbow experiences during the pitch hovers right around this failure region, hence why UCL injuries are so common^{20,45}. The type of ligament failure depends on the rate at which the strain is applied⁵¹. Noyes et al.⁵¹ found that at a slower stretch rate, only 29% of failures occurred at the ligament body, while 57% of failures were the cause of tibial avulsion. When the rate of strain increased, the data was almost reversed with 28% of failures happening at the insertion site (tibial avulsion) and 66% at the midsubstance. The same holds true for the UCL, which is why most ligament injuries occur as midsubstance tears, rather than avulsions. The site of the injury does have implications for recovery procedures, with tears occurring more distally usually requiring surgery²² (Frangiamore 2017).

Ligament Injury and Recovery

When damage to the ligament body occurs, it heals in a way that is similar to most other connective tissue. The ligament healing process is defined by three distinct phases: (1) the acute inflammatory phase, (2) the proliferation phase, and (3) the remodeling phase. The duration of each of these phases varies substantially, mostly dependent on the severity of the injury and the healing capacity of the tissue involved. In the case of the baseball pitcher, these

events ideally happen in the course of their 4-day rest period, and some players take measures to speed up this process such as icing their arm, or taking ibuprophen. Ensuring the arm is recovered from their last pitching bout before playing again helps reduce the risk of overuse injury.

The acute inflammatory phase is triggered immediately after injury, and can last over a week depending on the magnitude of injury, and the use of any anti-inflammatory measures¹². Common symptoms include heat, pain, and swelling, while platelets clot the wounded area to create a relatively weak fibrous scar. This clot creates a framework to release growth factors such as IGF-I (PDGF, TGF β) which initiates local inflammation. The inflammatory process cues the delivery of neutrophils and macrophages which remove injured tissue via phagocytosis. Days after the injury fibroblasts can be seen surrounding the injury to build an extracellular scar matrix. This initiates the proliferation phase (2-14 days) and is characterized by the deposition of collagen and the formation of granulation tissue. Granulation tissue is the building block for connective tissue, laying down blood vessels on the wound surface. During this phase there is also an influx of fibroblasts which are responsible for production of the components of the extracellular matrix, being mostly collagen and glycosaminoglycan. The remodeling phase (14+ days) sees an increase in collagen content and density, along with the re-alignment of collagen fibers.

Over a course of weeks, months, and even years, blood and other fluid gradually leave the wound leaving primarily fibroblasts where the scar once was. In a study with rabbits, structural properties of the MCL were measured during healing²⁵. He observed a significant initial increase in midsubstance cross sectional area, likely representing scar component

deposition. From 3 to 14 weeks, cross sectional area of the injury site decreased as the scar remodeled; but when tested again at 40 weeks, no further changes were seen in scar dimensions. Even after the 40 weeks of healing, the ligament was significantly thicker (greater CSA) than the uninjured control group. A healthy ligament is primarily type I collagen with highly organized fibers, and the scar begins to emulate this template during the remodeling process which can continue for months or years. Scars are built with many structural 'flaws', which are necessary for proliferation, however unsuitable for resisting heavy tensile loads. The remodeling process involves the transition of the healing process to once again becoming fully functional. Throughout this time, vascularity and fibroblast density decline in favor of increased collagen fibrils with better fiber alignment. The MCL has recovered to within 10-20% of normal viscoelastic properties, but still have inferior creep and stress relaxation characteristics. These changes help the ligament to regain some of its original strength, but a complete return of mechanical properties has not been demonstrated.

Although long-term ligament health is not being measured in this study, the findings are of great relevance to the professional baseball pitcher. The next section will discuss adaptations that occur to the medial elbow throughout a pitching career, some of which happen to coincide with the changes in ligament morphology after injury.

UCL Adaptations to Pitching

Due to the immense strains the medial elbow undergoes during the pitching motion, many physiological changes occur over a pitcher's playing career^{10,25,42}. Much of these changes

are due to repetitive traumas over an extended period, rather than a single event resulting in acute injury⁴⁴.

In 2003, Nazarian et al.⁴⁸ performed a study on 26 asymptomatic MLB pitchers, examining the morphological adaptations seen in the UCL of the throwing arm. Specifically, the thickness of the anterior band of the UCL, the ulnohumeral joint space, and other abnormalities such as hypoechoic or calcifications. They discerned these changes using dynamic ultrasonography, and used the non-throwing arm as a control measure. At rest, the mean thickness of the anterior band of the UCL in the throwing arm was significantly different, found to be 6.3mm +/- 1.1 in contrast to the non-pitching arm which was 5.3mm +/- 1.0 (p < .01). This discrepancy grew when a valgus force was applied to the arm. Valgus stress induced no change in mean thickness of the throwing arm (6.3mm +/- 1.4), but a decrease in thickness in the non-throwing arm (4.8mm +/- 0.9). This difference under valgus stress was even more significant than the findings at rest (P < .001).

TABLE 2
Morphologic Changes in Throwing Arm vs. Non-Throwing Arm⁴⁸

Test Variable	Throwing Arm	Non-Throwing Arm	P-Value
UCL Thickness (rest; mm)	6.3 ± 1.1	5.3 ± 1.0	P < .01*
UCL Thickness (stress; mm)	6.3 ± 1.4	4.8 ± 0.9	P < .001*
Joint Space (rest; mm)	2.8 ± 1.0	2.5 ± 0.7	P > .05
Joint Space (stress; mm)	4.2 ± 1.5	3.0 ± 1.0	P < .01*
Hypoechoic Foci	69% (18 of 26)	12% (3 of 26)	P < .001*
Calcifications	35% (9 of 26)	0% (0 of 26)	P < .001*

*denotes statistical significance

In addition to increased anterior band thickness, Nazarian et al.⁴⁸ found a significant difference in ulnohumeral joint space (when under valgus stress) between the pitching elbow

and the control (4.2mm +/- 1.5 vs 3.0 +/- 1.0, respectively; $P < .01$). All measurements were performed at 30 degrees of elbow flexion (Table 2). These observed changes in UCL morphology are of particular interest due to the fact that these participants were all asymptomatic, raising the question as to whether these differences are merely adaptations to the repetitive trauma of pitching, or if these are indications of accumulated damage, possibly requiring future surgical intervention. Interestingly, the hypoechoic foci and calcifications of the medial elbow seem to be correlated with both UCL thickness and joint space. Hypoechoic foci were seen in the anterior band in 18 of the 26 (69%) throwing arms, and in only three (12%) of the 26 non-throwing arms ($P < .001$). Calcifications were detected in nine throwing arms (35%), compared to zero of the non-throwing arms. 20 (77%) of the 26 pitching arms had either hypoechoic foci or calcifications. When this group was compared to the remaining six pitching arms without any abnormalities, some significant differences were evident. Mean ligament thickness (6.6mm vs 5.5mm, $P < .05$) and joint space width (1.3mm vs 1.0mm, $P < .05$) were both higher in pitchers displaying these irregularities. What's more, the combined hypoechoic foci and calcifications group had been playing at the professional level for a significantly longer time (8 years +/- 3.3 vs 4.7 years +/- 3.4; $P < .05$). These findings suggest that the longer a player participates at the professional level, the greater these differences will be.

Beginning in 2002, Ciccotti et al. performed a similar study with many more participants, and therefore much greater statistical power¹¹. Over a 10-year period, stress ultrasound examinations were performed on 368 asymptomatic professional baseball pitchers. Like the 2003 Nazarian et al.⁴⁸ study previously mentioned, both elbows were scanned for morphological differences, representing adaptations the UCL undergoes due to pitching. Once

again, significant alterations were seen in the pitching elbow including UCL thickening (6.15mm vs 4.82mm; $P < .0001$), greater ulnohumeral joint laxity (4.56mm vs 3.72mm; $P < .02$), and a higher prevalence of both hypoechoic foci (28% vs 3.5%; $P < .001$) and calcifications (24.9% vs 1.6%; $P < .001$). These findings provide fantastic statistical power to underline the results of prior work, as well as a foundation of baseline data for hundreds of professional pitchers. At the time of this study's publication, 12 of the 368 players who participated later suffered a UCL injury. The 12 players baseline measures were compared with the remaining 356 individuals. Although increases in all parameters were observed, none of them were significantly different from their uninjured counterparts. Post hoc analysis conceded that a sample size of 17 injured players would have resulted in statistical significance. Although conclusions are difficult to draw from insignificant statistical findings, this is of clinical importance as it may shed light on a link between these adaptations of the UCL and the potential for UCL injury.

While the adaptive changes of the medial elbow are well documented in professional pitchers, it is unknown when these changes begin to occur. In 2015, Marshall et al.⁴² investigated the initial stages of this adaptive process by examining the throwing and non-throwing arm high school pitchers. 22 asymptomatic high school pitchers were recruited, with a mean age of 16.9 years. Their results showed no significant difference in any of the 4 previously reported parameters (UCL thickness, joint laxity, hypoechoic foci, or calcifications) that are seen to deviate at the professional level. These findings suggest that players of such young age may not display morphologic changes of the elbow that are detectable with ultrasound technology. This is probably due to the relatively shorter playing career of a high school pitcher, and lower

tensile forces acting on the medial elbow when compared to an older and stronger professional player.

In 2016, Tajika et al.⁵⁹ performed a study similar to the 2015 Marshall⁴² study, however Tajika examined high school pitchers both with and without symptoms. 122 high school baseball pitchers were surveyed for any elbow pain experienced in the last 3 years. UCL thickness and ulnohumeral joint space were then recorded via gravity stress ultrasound on both elbows for all 122 participants at 30° of flexion. In contrast to the Marshall's findings, Tajika et al. observed a significant difference in UCL thickness between dominant (3.6mm +/- 0.8) and non-dominant arms (2.9mm +/- 0.6; P < .001). Secondly, there was a significant difference in UCL thickness between pitchers who had experienced elbow pain in the last three years and those who were asymptomatic. Pitchers who had experienced elbow pain had significantly thicker UCL (3.9mm +/- 0.9) than those without (3.4mm +/- 0.7; P = .0013). This correlation between symptom history and ligament thickening might suggest that the increase in cross sectional area is due to scar tissue accumulation rather than an adaptive increase in collagen content to better deal with the loads associated with pitching. An important distinction to make when considering these results is that the three-year symptom history was not specific to the medial elbow, but to the elbow as a whole.

With these studies in mind, there appear to be links between increased pitching volume, UCL thickness, and elbow symptom history. It is still unclear whether this thickening is an adaptive process (possibly due to the production of collagen), or a sign of accumulated damage. The question becomes, why is this ligament getting bigger, and is this a warning sign of future injury? A study by Ohno et al.⁵² in 1995 observed the healing capacity of the MCL in rabbits

after injury. They found that the cross-sectional area of the ligament was more than double that of the control group. This observation suggests that indeed this thickening of the UCL may be due to an accumulated level of damage from which the UCL has never fully been allowed to heal. If this were the case, the next logical question is what can we do to combat this accumulated fatigue and damage? One option might be to increase the number of rest days between games a starting pitcher plays in, but then, how much rest is necessary? Shear wave elastography may have the answer.

Shear Wave Elastography: Potential for Ligament Pathology Diagnosis

Ultrasound shear wave elastography is a relatively new tool for the quantitative evaluation of the mechanical properties of connective tissue *in vivo*^{7,37,53}. Initially, deformation must be created in the tissue which is done by sending a concentrated ultrasound beam to the target area, creating shear wave propagation. These shear waves spread transversely to the radiation force. Propagation speed is measured, which is then used to find the Young's Modulus of the tissue, one of the major parameters used to assess soft tissue elasticity and stiffness. The faster the velocity of the shear waves, the harder the surface of the tissue is. This can be useful for finding abnormalities such as tumors or inflammation which could cause changes in tissue elasticity, but may not be visible with ultrasound imaging³⁷. It is the current study's hope to broaden the clinical application of elastography. There have been many recent studies on its use in tracking tendon recovery post-surgery. However, very few have assessed its feasibility as a measurement for ligament health. The following papers delve into the progression of elastography as a tool for quantitative measurement of tissue elasticity.

Elastography was first coined in 1991 by Ophir et al.⁵³, who were performing a study on a new method for imaging the elasticity of biological tissues. Ophir used a method of elastography known as compression elastography, in which deformation is created via external compression (i.e. with the hands). “The method is based on external tissue compression, with subsequent computation of the strain profile along the transducer axis, which is derived from cross-correlation analysis of pre- and post-compression A-line pairs. The strain profile can then be converted to an elastic modulus profile by measuring the stresses applied by the compressing device and applying certain corrections for the non-uniform stress field,”⁵³. Essentially, the process applies a stress to the target tissue, then measures the displacement using ultrasound. Ophir demonstrated elastography’s efficacy in biological tissue by producing images of slabs of bacon. Bacon is a great test subject due to its striated nature of fat and muscle, which would provide two visibly distinctive tissues with different mechanical properties. The images show at least two stiff layers which probably correspond to the muscular tissue⁵³. Not only were they able to discern muscle from fat, but they noted a variance in compliance between fat layers.

Ophir pioneered the use of elastography using the compression technique (also known as *strain elastography*), and while the principles of elastography remain similar, the current study will be using the shearwave method for multiple reasons. Shearwave elastography is less dependent on researcher skill, as the deformation of the tissue is created by the ultrasound pulse rather than the researcher applying manual strain. Another limitation of the manual compression technique is that it can only show stiffness relative to the tissue surrounding it. In the example of Ophir using elastography on bacon, he would be able to see that the fat was less

stiff than the muscle according to the color coded elastogram, but wouldn't have a quantitative value for each tissue type. Shearwave elastography has the advantage of also identifying an objective quantitative value in kPa.

Ultrasound elastography may also have clinical applications for quickly and accurately assessing mechanical properties of the musculoskeletal system in vivo. Porta et al.⁵⁵ performed a study in 2014 to evaluate the feasibility and reproducibility of ultrasound elastography (Porta 2014). The researchers gathered 11 healthy participants who underwent US elastography examination on both patellar tendons at the proximal, middle, and distal portions of the tendon. The study also used two separate sonographers in order to compare inter-operator discrepancies. Three trials were averaged for each of the three portions of the patellar tendon, totaling in 198 examinations per operator. The study found good values of intra-observer agreement (Operator 1: P-values = 0.790, 0.864, 0.865; Operator 2: P = 0.642, 0.882, 0.613; for proximal, middle and distal portions, respectively), and inter-observer (P = .657) agreement. Inter-observer analysis also showed high agreement values at each individual portion of the tendon (proximal: P < 0.001, middle: P = 0.001, distal: P = 0.005). Duration of the examinations were also recorded to better determine the feasibility of clinical use. The mean time to perform the ultrasound elastography evaluation with an inexperienced operator was 5 minutes. However, as the operator grew more familiar with the procedure, duration dropped to 2 minutes. Being both reproducible and feasible, it appears ultrasound elastography could be a valuable tool in assessing healthy patellar tendons. However, more work needs to be done to better define the possibility for pathology diagnosis.

This possibility, it seems, is already providing much promise. In 2016, Busilacchi et al.⁹ utilized elastography as a technique for following up on Achilles tendon surgery. They recruited 25 subjects from 2011 to 2013, all of which had recent operations. Stiffness was measured in a “strain index” (SI) to represent tendon elasticity, with lower scores meaning higher stiffness. The first strain index measurement of each subject was taken 40 days after surgery, then subsequently 6 months, and 1 year. They found that as the tendon heals, it becomes increasingly more stiff, particularly at the myotendinous junction, and at the site of the suture. They found that the SI of all three examination sites decreased with a significance of $P < .001$. Interestingly, the stiffness rose above the contralateral (uninjured) Achilles tendon stiffness, as well as a control group of 60 tendons from 30 healthy volunteers. This increasing stiffness in healing Achilles tendon correlated to an increase in ATRS scores, a common questionnaire following Achilles tendon surgery. This successful application of elastography as a method for tendon mechanical property evaluation leaves many questions about the potential for elastography in the role of diagnosing ligament injury.

At the time of the current study, very little research has been published on the use of shearwave elastography in the diagnosis of ligament injury. Nothing could be found on the UCL or other commonly studied ligaments in the body such as the ACL or MCL. However, it has been used to measure the elasticity of the coracohumeral ligament (CHL) in people presenting symptoms of frozen shoulder (adhesive capsulitis) such as the decreased range of motion of the humerus in external rotation. In 2015, Wu et al.⁶⁴ gathered 9 men and 11 women presumed to have adhesive capsulitis, and examined the CHL for differences in mechanical properties when compared to a control of 30 healthy men and women. In all subjects, moving the arm from

neutral position to maximal external rotation of the humerus increased the elastic modulus of the CHL ($P < .001$). This increased elastic modulus with increased tissue strain is what we would expect to see as ligament crimp is unwound, and the collagen fibers of the ligament are pulled tight. When comparing affected and non-affected arms of the participants, significant differences were noted. At shoulder neutral position, the median value of the symptomatic shoulder was 234.8 kPa, relative to the 203.3 kPa modulus of the healthy shoulder ($P = .004$). In addition, when both arms were externally rotated to the maximal angle at which the affected arm could muster, the elastic modulus was greater in the symptomatic shoulder ($P = .005$). These findings show elastography can be a predictive measurement of ligament pathology, by calculating differences in the elastic modulus of tissue in vivo.

Perhaps more contextually relevant to the current study is the work of Lustgarten et al.^{38,39}, and their observations in the healing process of ligaments in the equine distal limb. In 2015, they investigated the capacity of shear wave elastography to reveal acute lesions that occurred within 2 weeks of imaging, and chronic lesions which occurred more than 2 weeks beforehand. Lesions were initially diagnosed and confirmed by magnetic resonance imaging (MRI) and ultrasound (US). In 57 horses with 65 lesions, acute lesions were found to be significantly softer ($P < .0001$), than chronic lesions ($P < .0001$). Stiffness of the lesions was also found to increase significantly throughout the healing process ($P = .0136$). In addition, they reported that more hypoechoic regions (areas which reflect relatively few ultrasound waves) appeared softer ($P = .0087$), and more hyperechoic regions presented tougher ($P = .0002$). This study suggests elastography has the ability to detect soft tissue injuries in the distal limb of the equine athlete³⁸. It is the hope of the current study to expand upon this assertion and evaluate

its use in human participants. Although shear wave elastography has many promising applications, it does have its limitations.

The application of ultrasound elastography faces a challenge in that there are a number of different techniques and processing algorithms that are capable of creating elastographic images¹⁵. This creates unwanted variance and lack of repeatability when laboratories studying similar fields use different techniques. Reports, limitations as well as artefacts may be specific to these different methods of elastography. Due to the current study's use of shear wave elastography (SWE), it has been the main focus for this literature review. Other common techniques include sonoelastography (also known as real-time elastography), acoustic radiation force impulse, and transient elastography. One problem they all face is optimizing the distance between the probe and the tissue of interest. "In many musculoskeletal applications, the tissue of interest is very superficial or even lies directly under the skin", for example the Achilles tendon¹⁵. A minimum distance of 1.2mm is usually necessary for the ultrasound system to produce the elastogram. This can lead to problems with very skinny people, or when targeting very superficial tissue. It is sometimes necessary to use a probe adaptor to further separate the tissue of interest and the probe¹³.

Another source of experimental variance comes from the size of the elastogram. Elasticity of the target tissue is displayed relative to the elasticity of the surrounding tissue in the frame of the picture. This means variations in the stiffness of the structures around the area of interest will affect the appearance of the area itself. In musculoskeletal application, a wide range of mechanical properties exists between muscle, tendon, fat, and bone. As the literature on elastography grows, specific image parameters should be made for assessment of different

structures so as to create a standard for elastogram production. Although there has been much success in the early studies of elastography, one major concern still remains. In many cases, experiments are run by testing the capacity of elastography to identify pathologies that were first confirmed with MRI or greyscale US. To the author's knowledge, there are no studies that have shown elastography to discover symptomatic musculoskeletal pathologies that are not visible to US or MRI. Until it is demonstrated that elastography can reveal musculoskeletal pathology which standard image processing methods cannot, clinical application will be low. The current study may help to shed light on this question.

Summary

Shear wave elastography has been shown to have the ability to detect short term (< 2 weeks) changes in ligament stiffness in horses³⁸. It has also been shown to quantify differences in coracohumeral ligament stiffness between patients with adhesive capsulitis, and healthy participants⁶⁴. It is the purpose of the current study to build off of these two studies and determine if shear wave elastography can be used to measure short term changes in mechanical properties of the UCL, if changes in the UCL are indeed occurring. The standard rest protocol for starting pitchers in professional baseball is usually 4 or 5 days before pitching another game. This allotment of time appears to be the consensus of baseball experts with regards to the amount of healing time is required after a starting pitching bout. With the rate at which Tommy John's surgery is increasing, it may be time to reevaluate the necessary days off between games started, and to explore the possibility that team managers may be sending pitchers back to the plate too soon. The current study proposes the use of the shear wave

elastography as a method to quantify the short term material properties of the UCL in college baseball pitchers.

METHODS

Introduction:

This study used shear wave elastography to measure changes in ligament stiffness of the UCL in collegiate baseball pitchers. Stiffness measurements were taken both before and after the pitching bout. One measurement was taken on the day prior to the pitching bout, in addition to daily measurements on the four days following the pitching bout. A total of 5 measurements were taken on each player, each on a separate day. All procedures were approved by the University Internal Review Board.

Exclusion Criteria:

1. Previously diagnosed partial or complete tear of the UCL
2. Previous elbow surgery
3. Previously diagnosed abnormality of the UCL

Participants:

The participants in this study are comprised of 6 collegiate baseball pitchers. Demographic and follow-up throwing load data was collected using the Demographics and Throwing Load Questionnaire (Appendix A). Recent throwing load and throwing arm health information was collected using the KJOC questionnaire (Appendix B) on the day of the initial baseline measurement.

The Kerlan-Jobe Orthopedic Clinic Overhead Athlete Shoulder and Elbow score is a 13-item self-reported questionnaire which was developed specifically for the overhead throwing athlete by one of the premier research centers in sports medicine. It has been validated by the American Shoulder and Elbow Surgeons scale⁵⁰, and the Disabilities of the Arm, Shoulder and Hand score^{2,14}. With its questions directly pertaining to overhead athletes, it is commonly used in baseball studies as a measure of throwing arm health^{49,62}. In the current study, this questionnaire was administered on the day of the baseline stiffness reading, in an attempt to quantify each player's current health status.

Throwing Protocol:

Throwing sessions were conducted in accordance with the pitchers current training program as either an in-game starting pitching bout, or a bullpen session during practice. However, if it were a bullpen session, to count as a valid throwing bout the pitchers were required to throw at least 50 pitches. All participants who pitched in-game threw more than 50 pitches. Pitchers threw a combination of fast-balls and breaking-balls in similar fashion to their standard bullpen sessions, the exact number of each were recorded. Participants were instructed to practice as if the researchers were not there at all. In order to observe material property changes in the UCL that would likely occur in a game scenario, it is important that the participant is throwing at or near 100% effort. To evaluate effort, comparisons were made between estimated fast-ball speed, and observed fast-speed. Before throwing, pitchers were asked to estimate their fast-ball speed, and if fast-ball pitch mean velocity was not within 10% of the estimated max pitch velocity, the session was repeated on a different day. Pitch velocity was measured with a Bushnell Speed Radar Gun (model# 101911).

Equipment and Instrumentation:

Shear wave elastography and B-mode images were analyzed using the Supersonic Aixplorer MultiWave SSIP90029 (SuperSonic Imagine, S.A., Aix-en-Provence, France). Images were collected using a SuperLinear™ SL15-4 musculoskeletal transducer (SuperSonic Imagine, S.A., Aix-en-Provence, France). During the stiffness measurements, participants' arms were supported using a custom-built splint with adjustable width to secure the arm in position. The splint will help to ensure 30° of flexion at the elbow is maintained throughout the examination, and that the UCL is the primary restraint to valgus stress. A Seca 703 digital scale (Seca gmbn & Co.kg, Hamburg, Germany) was used to measure height in meters and weight in kilograms.

Measurement Protocol:

Prior to imaging, participants read and signed the Informed Consent Document (Appendix C), and their height and weight were recorded. Stiffness measurements were taken the day before the pitching bout, as well as the following 4 days, but not on the day of the pitching session. Pragmatic reasons dissuade taking measurements the same day as the pitching bout, as well as the unknown effect of swelling on shear wave elastography precision. This 4-day observation protocol was chosen to reflect the typical number of rest days allotted to a player between consecutive pitching bouts (generally 4 days off). Elbow circumference measurements were taken distal to the elbow joint to measure swelling.

The data collection schedule was designed as follows:

Day -1	Day 0	Day 1	Day 2	Day 3	Day 4
Initial Stiffness Measurement	Pitching Bout	Follow-Up Stiffness Measurement 1	Follow-Up Stiffness Measurement 2	Follow-Up Stiffness Measurement 3	Follow-Up Stiffness Measurement 4

Ultrasound elastography stiffness readings were taken while the participants lay supine with the humerus externally rotated, and the elbow flexed 30 degrees, as described by Nazarian et al. in 2003. The arm was supported by a custom-built splint with adjustable-width arm positioning, holding the arm in place while the examination is done. Arm movement was restricted by sliding arm supports with neoprene straps secured over the splint. To apply tension to the UCL and remove any collagen crimp, the participants held a 1-kg weight throughout the examination. This ensures stiffness readings were taken from the linear region

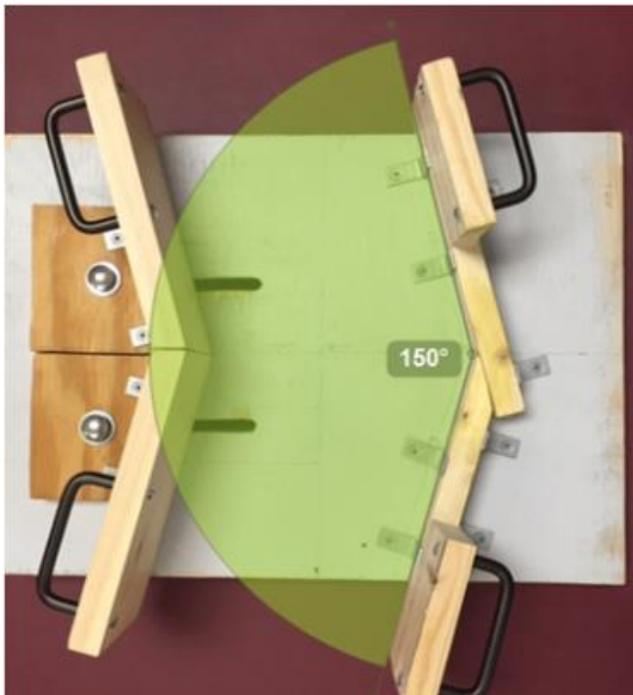


Figure 1: Custom built splint to maintain participant's arm at 30 degrees of flexion.

of the UCL stress-strain curve. Participants were cued to loosely grip the weight as opposed to tightly gripping, allowing the wrist to extend naturally and help prevent muscle guarding. They were also instructed to maintain a neutral wrist position, avoiding pronation/supination and radial/ulnar deviation. To further reduce unwanted muscle tension during the measurement, stiffness measurements were not taken

during the first few minutes of the examination, and light conversation was employed to calm the participant. It is our hope this helped make the participant feel at ease, and more relaxed.

Ligament stiffness readings were taken directly over the ulnohumeral joint gap with the ultrasound probe oriented parallel to the axis of the anterior bundle of the UCL to permit ideal shear wave propagation (Figure 5). The range of stiffness values during elastography readings

was set from 0 to 600 kPa.

Stiffer structures are displayed with a red overlay, while blue coloring highlights less-stiff structures.

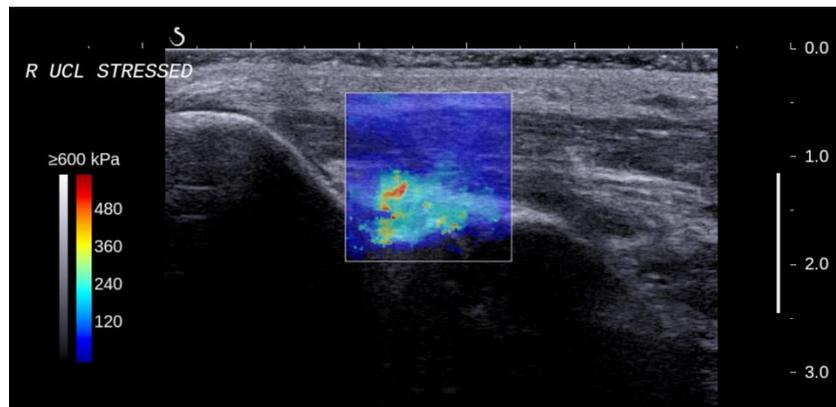


Figure 2: Elastogram of the UCL. Stiffer structures are in red, less stiff in blue.

The data collection protocol was comprised of 2 different conditions in which the medial elbow was examined (Figure 6). During both conditions, the subject held a 1kg weight in the pitching hand. In the first condition, the arm was supported by a wooden plank,

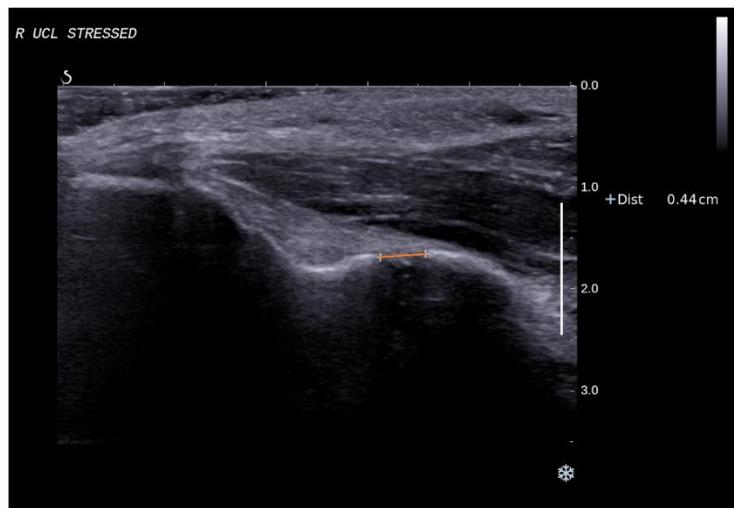


Figure 3: Ulnohumeral joint space measured with the distance tool on the ultrasound machine.

reducing the tension on the UCL. B-mode images of the ulnohumeral gap were taken, representing a “supported” state of the medial elbow. This arm support was removed for the

second condition, representing a “stressed” state of the medial elbow. The difference between the two, or change in ulnohumeral joint space, represents joint laxity. As UCL stiffness changes occur, joint laxity should theoretically mirror these changes by showing increased joint laxity with decreased ligament stiffness.

Data Processing:

Data reduction was completed on the same Aixplorer ultrasound elastography machine used to acquire the images. The Distance tool was used to measure ulnohumeral gap space, while the Q-box tool processes the stiffness readings. Joint space measurements were reported as the distance between the trochlear notch of the ulna, and the trochlea of the humerus. The Q-box measurement tool allows for site-specific stiffness readings by providing a small circular region of interest which can be manipulated by the user. Once the desired position and size of the Q-box are entered, the mean, minimum, maximum and standard deviation stiffness values are calculated in kPa for the area within the Q-box region.

Stiffness readings were taken at 4 points (between 40% and 80% of the length of the ligament) and averaged to calculate the mean stiffness of the UCL for that trial. The position of these points was determined by evidence of strong

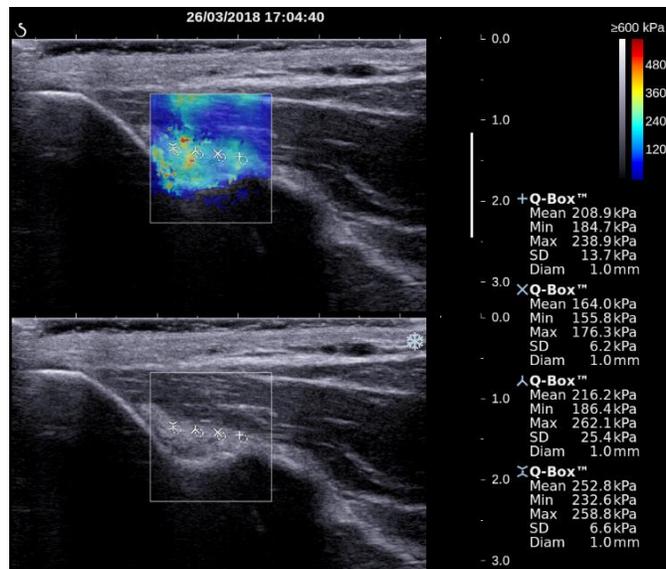


Figure 4: The Q-Box tool was used to calculate stiffness within the region of interest.

shearwave propagation. The criteria for placement of the Q-box regions was: 1) area had clear distinction between ligament and surrounding tissue, 2) no gaps were present in the elastogram superficial to the UCL, 3) Q-box regions would be placed on regions representative of the whole ligament. If a very small part of the ligament had an extreme measure of stiffness, that part was avoided as to preserve the consistency of measurements, and to avoid the mean being thrown off by an outlier. 3 trials were completed each day, and the mean of all 3 trials was reported as the stiffness measurement for that day.

Reliability Study:

Below is the data from a reliability study performed in the ECU Biomechanics Lab by the same sonographer used in the current study (unpublished work).

TABLE 3
Reliability of SWE Measurements of the UCL in Healthy Controls

	Day 1	Day 2	Day 3	Day 4	Day 5	Mean	SD
Sub 1	193.85	216.35	269.38	225.34	209.44	222.87	28.43
Sub 2	265.15	221.02	210.18	222.76	230.93	230.01	20.99
Sub 3	222.48	206.65	239.83	305.38	235.34	241.94	37.74
Sub 4	206.53	237.64	225.53	250.12	204.04	224.77	19.82
Sub 5	234.69	231.38	195.73	256.28	235.98	230.81	21.92

This work shows the amount of daily fluctuation that one might expect to see in the stiffness of the UCL in healthy non-baseball players. The mean of within-subject standard deviations was 25.7kPa. This gives us an idea of the types of changes which are meaningful, and the types of changes which could be attributed to measurement error, or daily fluctuation of material properties.

Statistical Analysis:

With a sample size of only 6 pitchers, potential for statistical analysis was limited. Therefore, we used primarily descriptive statistics to assess changes that occurred throughout the study. A paired student's t-tests was used to analyze differences in mean stiffness changes between days, exploring the time effect on ligament stiffness. Specifically, we looked at Day -1 (the day before the game), Day 1 (the day after the game), and Day 4 (the fourth and final day of rest). These days were chosen because they represent crucial stages in throwing arm recovery. Day -1 represents the ligament at assumed full health, as the pitcher would be playing the following day. Day 1 reflects the changes in ligament stiffness that occur post-intervention (game scenario pitching bout). Days 2-4 represent the recovery process, with the final day of the examination displaying a return to regular health status.

RESULTS

Participants

The mean age of the pitchers was 19.83 years. The mean height and weight of the players was 1.83 meters and 92.98 kilograms respectively, resulting in an average BMI of 27.74. Of the 6 pitchers, 5 were right handed and 1 was left handed. The average baseball experience was 12.33 years (Table 4).

TABLE 4
Participant Demographic Information

	Mean	St. Dev.
Age (years)	19.83	2.32
Height (m)	1.83	0.06
Weight (kg)	92.98	13.96
BMI (kg/m ²)	27.74	4.61
Years Played	12.33	3.39

KJOC Scores

The average KJOC score of all six participants was 81.85 (Table 5). This Visual Analog Score was quantified in centimeters based on where the participant marked an “x” on a 10cm line. Higher values represent a healthy arm, while lower values indicate a potential concern. The questionnaire in its entirety is attached (Appendix B).

TABLE 5
KJOC Elbow and Shoulder Health Questionnaire Scores

Question (Visual Analog Scale)	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6
Difficulty warming up	10.0	7.3	10.0	9.0	10.0	3.4
Arm Pain (10 = none in competition, 0 = pain at rest)	6.8	2.0	10.0	7.0	10.0	4.7
Weakness/Fatigue in arm	10.0	3.5	10.0	3.0	10.0	8.9
Instability/Fatigue during competition	8.3	8.8	10.0	6.1	10.0	10.0
Relationship with Coaches affected by arm health	10.0	9.5	6.7	9.2	10.0	10.0
Required Pitching Motion Adjustments due to health	6.4	6.6	10.0	9.6	10.0	10.0
Velocity/Power limited by arm health	8.9	5.0	10.0	5.1	10.0	10.0
Throwing endurance limited by arm health	2.0	5.8	8.5	6.8	10.0	10.0
Control of pitch limited by arm health	9.1	4.5	8.0	7.4	10.0	10.0
Current competitive level limited by arm health	10.0	7.2	10.0	6.0	10.0	10.0
<i>KJOC Cumulative Score</i>	81.5	60.2	93.2	69.2	100	87

Which best describes your current status?

Playing without any arm trouble	X		X		X	X
Playing, but with arm trouble		X		X*		
Not playing due to arm trouble						

* Subject described arm trouble as a "non-issue"

UCL Stiffness Measurements

Mean UCL stiffness increased the first day following the pitching bout at 262.97 kPa (Table 6). This reflects a 30.67 kPa increase from baseline (1.2 standard deviations), or a 12.76% change (Table 7). UCL Stiffness declined approximately linearly over the following 3 days reaching a low of 218.34 kPa on the fourth day of recovery, dropping 13.96 kPa below baseline. No significant differences were found between baseline stiffness, the first day of recovery, and the fourth day of recovery (Table 8). A regression line was calculated in Figure 3 to show the slope of the linear rate of change in tissue stiffness throughout the rest period.

TABLE 6
UCL Stiffness Before and After Pitching Bout (kPa)

	Baseline	Day 1	Day 2	Day 3	Day 4
Subject 1	239.76	255.08	218.37	174.52	178.17
Subject 2	215.26	151.83	217.89	237.02	199.98
Subject 3	245.87	250.60	238.78	266.90	240.18
Subject 4	195.06	277.13	256.00	278.25	245.73
Subject 5	269.08	389.41	308.20	218.19	227.42
Subject 6	228.78	253.75	265.08	199.04	218.57
Mean	232.30	262.97	250.72	228.98	218.34
Std. Deviation	25.62	75.95	34.07	39.77	25.54
S.E. Mean	10.46	31.01	13.91	16.23	10.42

TABLE 7
Standardized UCL Stiffness Change Following Pitching Bout (% of Baseline)

	Day 1	Day 2	Day 3	Day 4
Subject 1	6.39	-8.92	-27.21	-25.69
Subject 2	-29.47	1.22	10.11	-7.10
Subject 3	1.93	-2.88	8.55	-2.31
Subject 4	42.08	31.24	42.65	25.98
Subject 5	44.72	14.54	-18.91	-15.48
Subject 6	10.92	15.87	-13.00	-4.46
Mean	12.76	8.51	0.37	-4.85
Std. Deviation	27.66	14.79	25.54	17.37

TABLE 8
Paired Comparisons of Stiffness Before and After Pitching Bout (kPa)

	Mean	Std. Deviation	S.E. Mean	95% C.I.		T-test	Sig. (2-tailed)
				Lower	Upper		
Baseline vs. Day 1	-30.67	64	26.13	-97.83	36.49	-1.174	0.293
Day 1 vs. Day 4	44.63	70.51	28.79	-29.37	118.62	1.55	0.182
Baseline vs. Day 4	13.96	38.2	15.59	-26.13	54.05	0.895	0.412

Figures 5 and 6 show the mean change in stiffness across the study timeframe of all 6 pitchers. The two figures show mean stiffness of the sample rising after the pitching bout approximately 30kPa, or 12%, then dropping back toward baseline by Day 3.

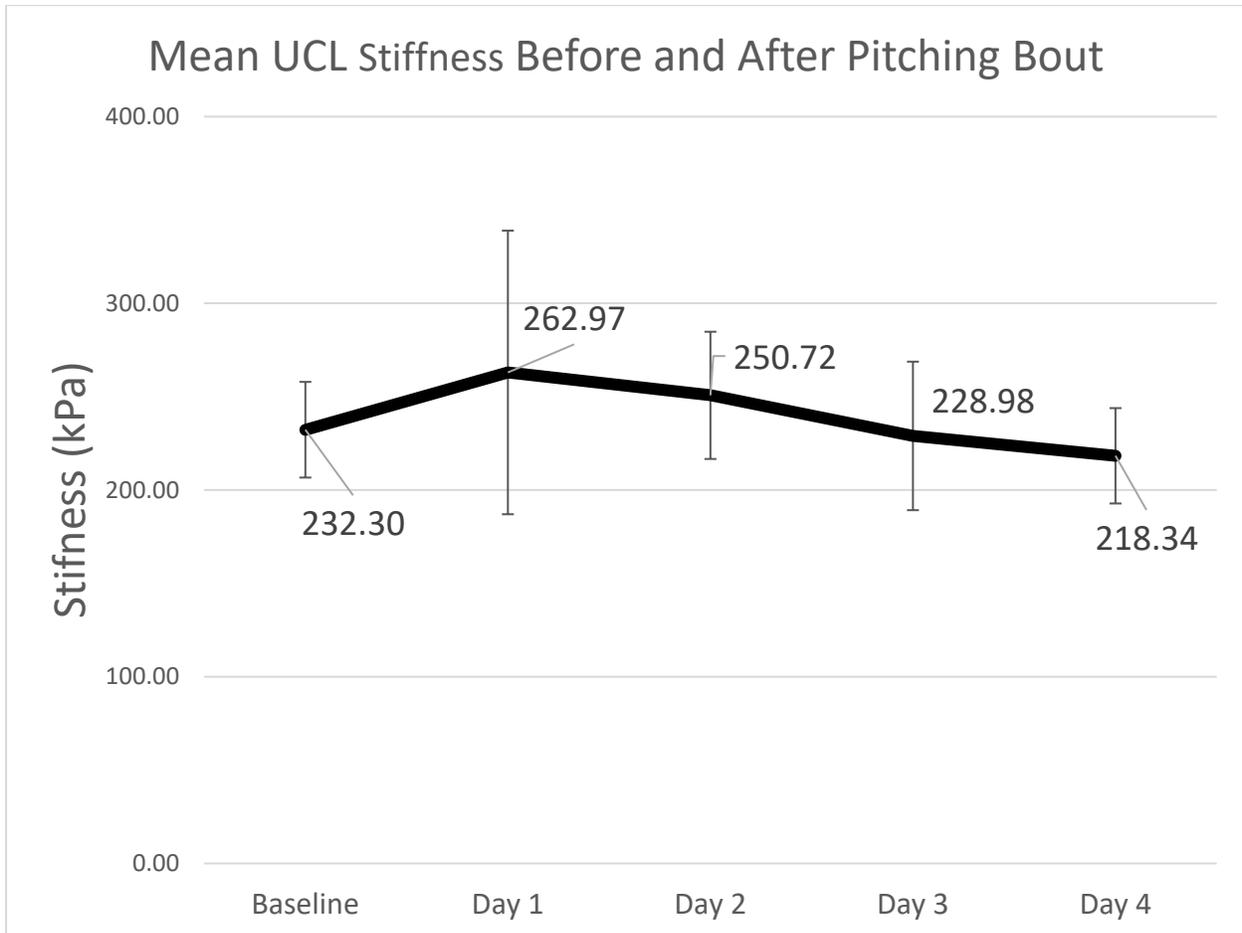


Figure 5: Mean UCL stiffness of all subjects across the study timeframe. Stiffness trended upwards after the pitching bout, then declined back towards baseline throughout the 4-day rest period. Mean is presented with standard deviation bars.

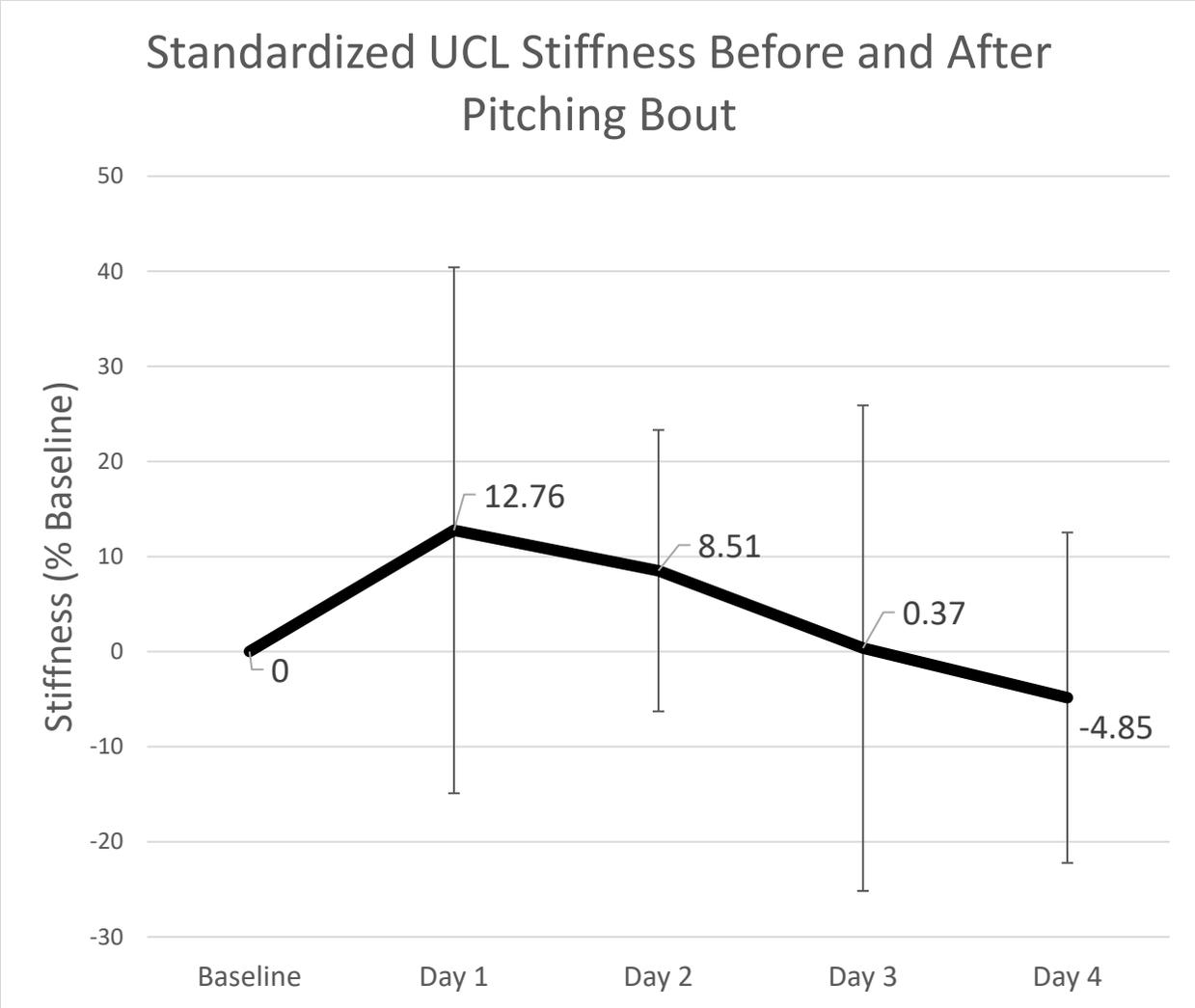


Figure 6: Standardized mean UCL stiffness of all subjects across the study timeframe. Changes are reported as a percentage of baseline measure. Mean is presented with standard deviation bars.

Figures 7 and 8 show stiffness changes of each individual subject. Visualization of the data shows a clear outlier in subject 2's stiffness response to the pitching bout. In both absolute and relative measures, subject 2 starkly contrasts the pattern seen in the other participants. Rest Day 1 saw the most variability in stiffness (standard deviation of 75.95kPa), while Baseline and Day 4 saw the least variance (standard deviations of 25.62 and 25.54 respectively).

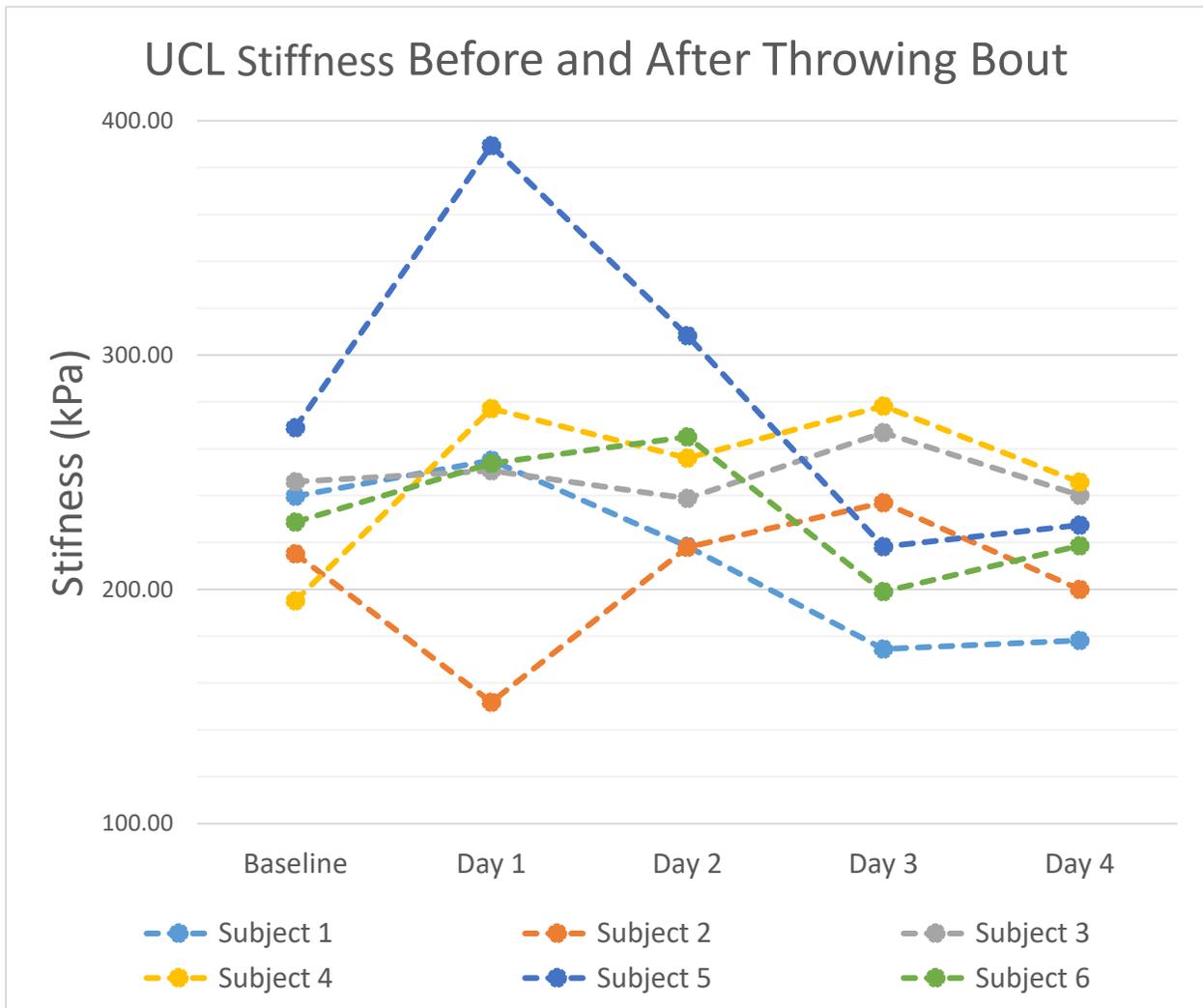


Figure 7: UCL Stiffness of each subject across the study timeframe.

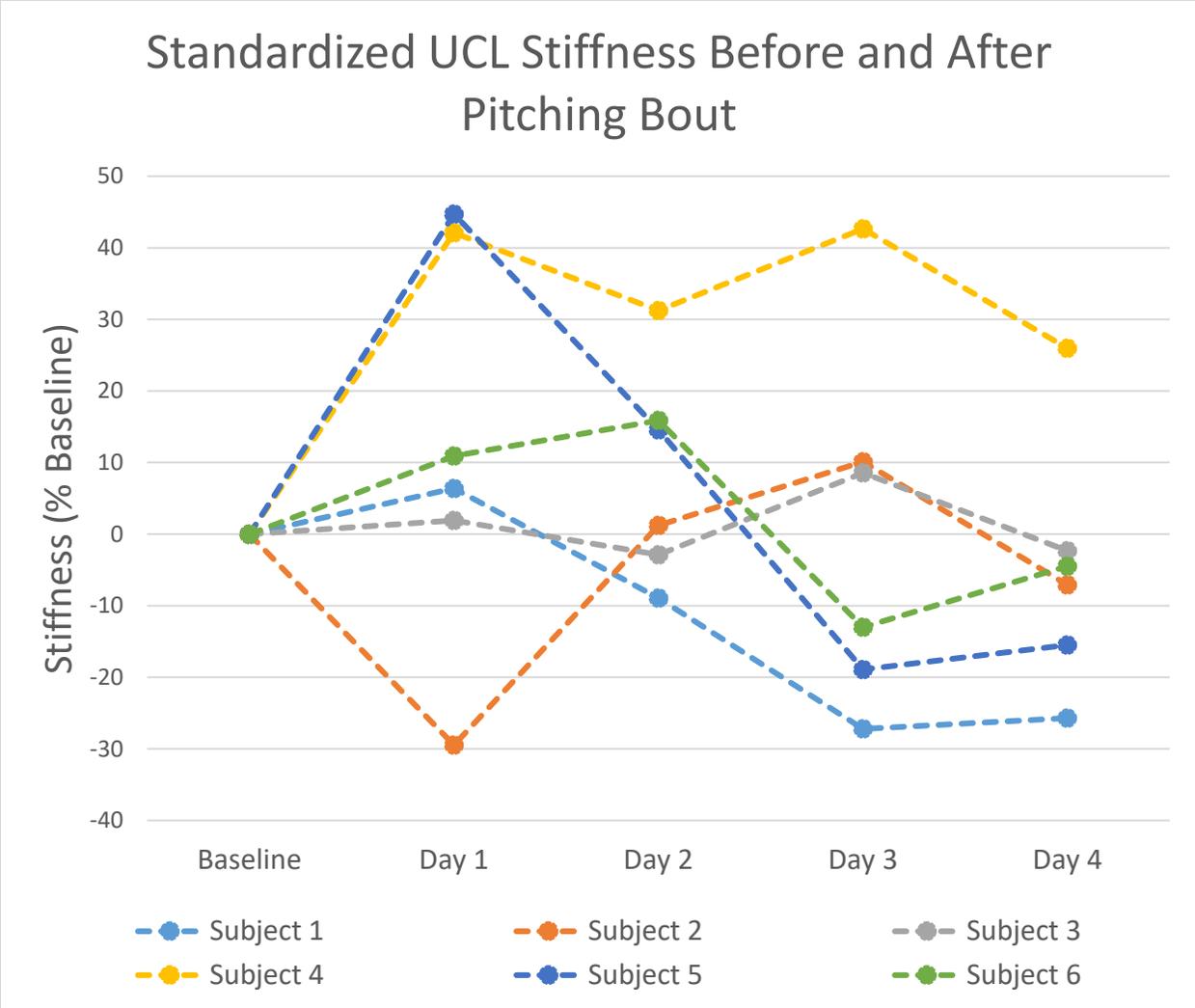


Figure 8: Standardized UCL stiffness of each subject across the study timeframe reported as percentages of baseline.

Linear regression was applied to demonstrate the daily change in stiffness the ligaments experienced throughout the rest period (Figure 9). The coefficient of determination was low, showing a very weak correlation between time and stiffness. Regression was also done on standardized values (Figure 10), with similarly low correlation.

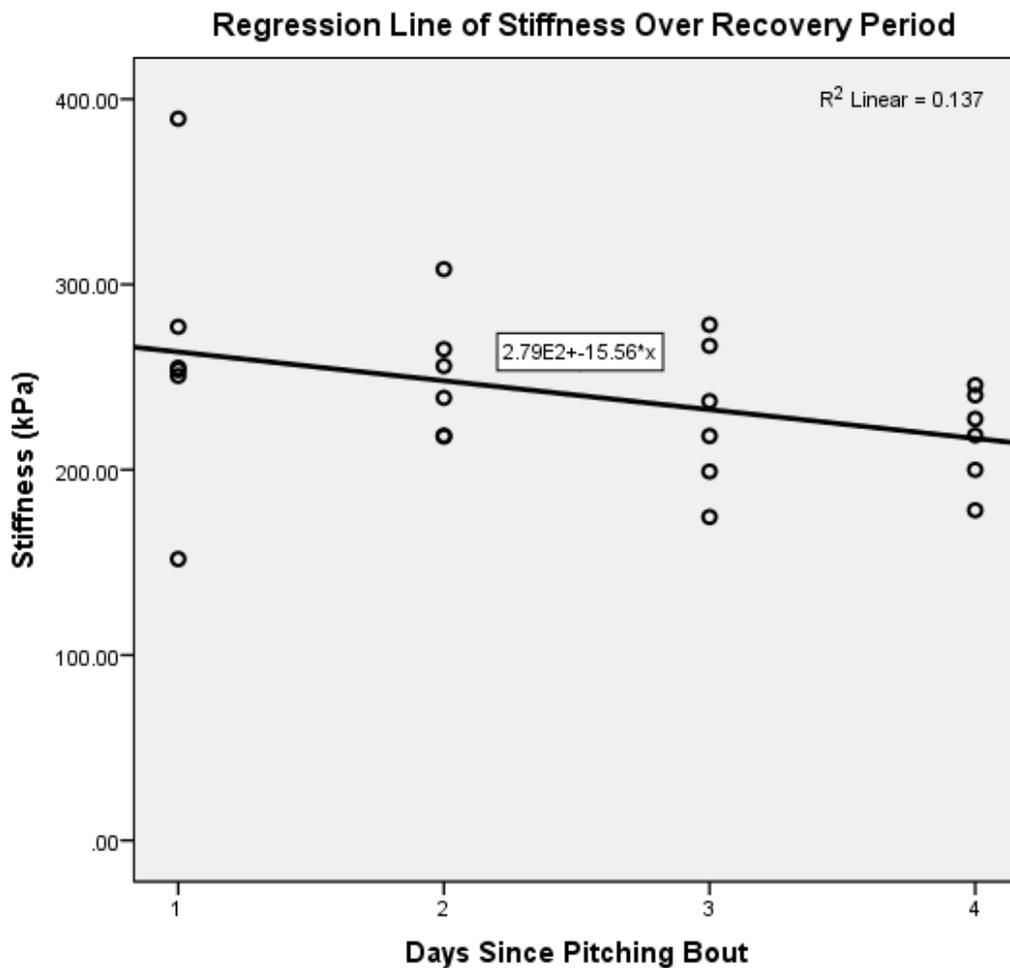


Figure 9: Regression line of UCL stiffness over 4-day rest period. The regression was not significant at the 0.05 level.

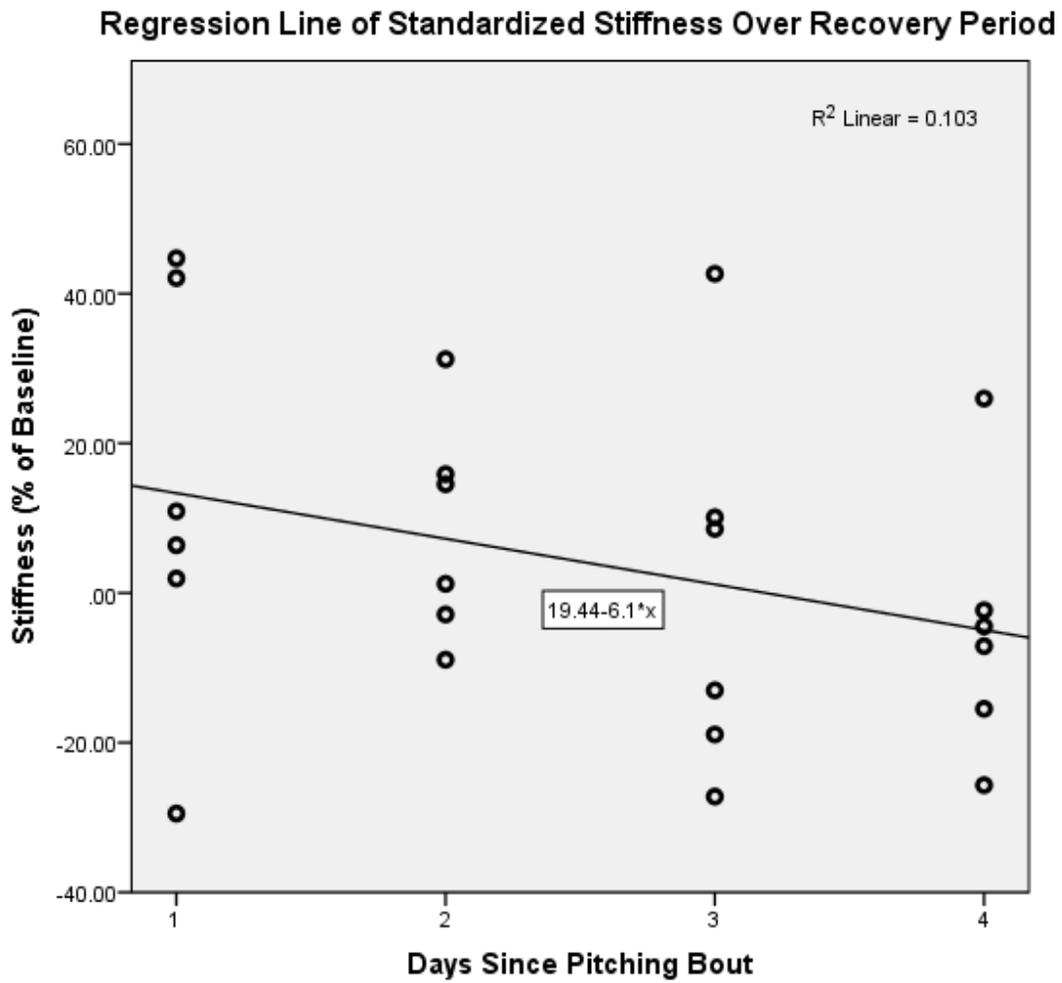


Figure 10: Regression line of UCL stiffness over 4-day rest period. The regression was not significant at the 0.05 level.

Change in Ulnohumeral Gap Space

Difference in ulnohumeral gap space was highest at baseline (mean = 0.64mm, standard deviation 0.63), however no significant differences were observed between days (Table 13). A high degree of variance was seen both within and between subjects. Table 9 shows ulnohumeral gap space in the supported position, where the UCL is not loaded. Table 10 shows joint space in the stressed condition, using a 1kg weight to provide valgus stress to the medial elbow. Table 11 is the difference between the two, showing the change in joint space (stressed condition – supported condition). Standardized values for change in joint space are reported (Table 12).

TABLE 9
Ulnohumeral Gap Space Before and After Pitching Bout (Supported Condition; mm)

	Baseline	Day 1	Day 2	Day 3	Day 4
Subject 1	5.20	5.50	5.57	5.50	5.90
Subject 2	4.53	3.93	3.87	4.37	4.13
Subject 3	3.23	3.83	3.33	3.50	3.00
Subject 4	3.07	3.07	3.10	3.17	3.73
Subject 5	3.03	2.77	2.67	3.00	2.80
Subject 6	4.37	3.70	4.10	4.53	3.43
Mean	3.91	3.80	3.77	4.01	3.83
Std. Deviation	0.92	0.95	1.02	0.96	1.12
S.E. Mean	0.37	0.39	0.42	0.39	0.46

TABLE 10
Ulnohumeral Gap Space Before and After Pitching Bout (Stressed Condition; mm)

	Baseline	Day 1	Day 2	Day 3	Day 4
Subject 1	5.67	6.47	5.90	5.97	6.03
Subject 2	5.03	4.93	4.73	5.07	5.13
Subject 3	3.50	3.73	3.90	3.50	3.60
Subject 4	3.27	2.97	3.00	3.03	3.30
Subject 5	4.93	3.07	3.33	3.10	3.37
Subject 6	4.87	4.93	4.53	5.10	5.00
Mean	4.55	4.35	4.23	4.30	4.41
Std. Deviation	0.95	1.35	1.05	1.24	1.14
S.E. Mean	0.39	0.55	0.43	0.51	0.47

TABLE 11
Difference in Ulnohumeral Gap Space (Stressed vs. Supported condition; mm)

	Baseline	Day 1	Day 2	Day 3	Day 4
Subject 1	0.47	0.97	0.33	0.47	0.13
Subject 2	0.50	1.00	0.87	0.70	1.00
Subject 3	0.27	-0.10	0.57	0.00	0.60
Subject 4	0.20	-0.10	-0.10	-0.13	-0.43
Subject 5	1.90	0.30	0.67	0.10	0.57
Subject 6	0.50	1.23	0.43	0.57	1.57
Mean	0.64	0.55	0.46	0.28	0.57
Std. Deviation	0.63	0.59	0.33	0.34	0.69
S.E. of Mean	0.26	0.24	0.14	0.14	0.28

TABLE 12
Standardized Ulnohumeral Gap Difference Before and After Pitching

	Day 1	Day 2	Day 3	Day 4
Subject 1	107.14	-28.57	0.00	-71.43
Subject 2	100.00	73.33	40.00	100.00
Subject 3	-137.50	112.50	-100.00	125.00
Subject 4	-150.00	-150.00	-166.67	-316.67
Subject 5	-84.21	-64.91	-94.74	-70.18
Subject 6	146.67	-13.33	13.33	213.33
Mean	-2.98	-11.83	-51.35	-3.32
St. Dev.	135.23	94.76	80.89	190.46

TABLE 13
Paired Comparisons of Difference in Ulnohumeral Gap Space (Stressed vs. Supported; mm)

	Mean	Std.	S.E.	95% C.I.		T-test	Sig. (2-tailed)
	Difference	Deviation	Mean	Lower	Upper		
Baseline vs. Day 1	0.089	0.869	0.355	-0.823	1.001	0.251	0.812
Day 1 vs. Day 4	-0.022	0.543	0.222	-0.592	0.548	-0.1	0.924
Baseline vs. Day 4	0.067	0.867	0.354	-0.845	0.977	0.188	0.858

No significant differences in joint space were seen between days. Table 13 shows very high p-values, indicating our results were far from statistical significance. Figures 11 and 12 show the mean joint space change across the study timeframe. Mean ulnohumeral gap space decreases slightly after the pitching bout but reaches its lowest point on Day 3 of the rest period. The difference between baseline and Day 3 was also insignificant ($p = 0.293$).

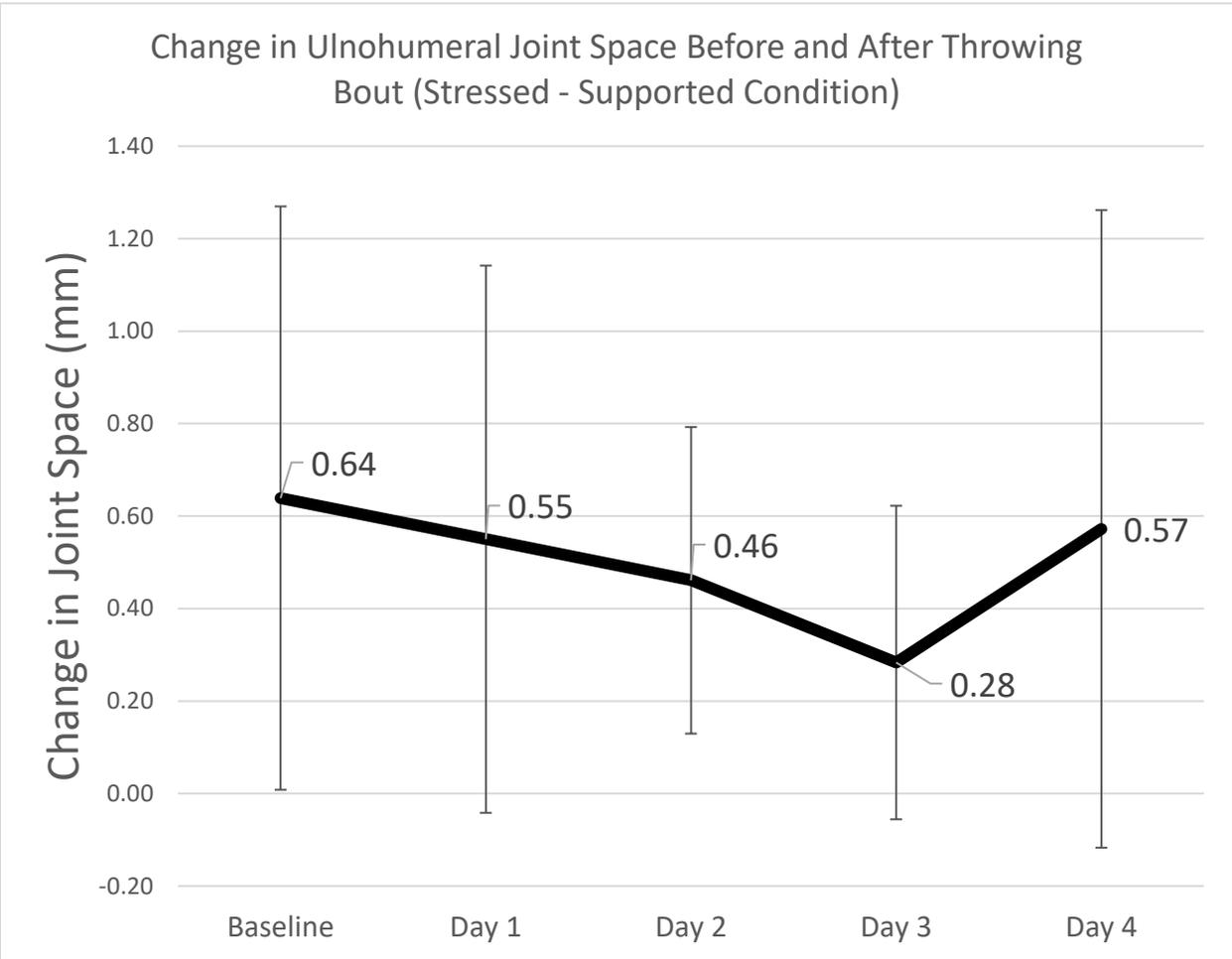


Figure 11: The mean difference between ulnohumeral gap space in the supported condition vs. stressed condition. Mean difference is presented with standard deviation bars.

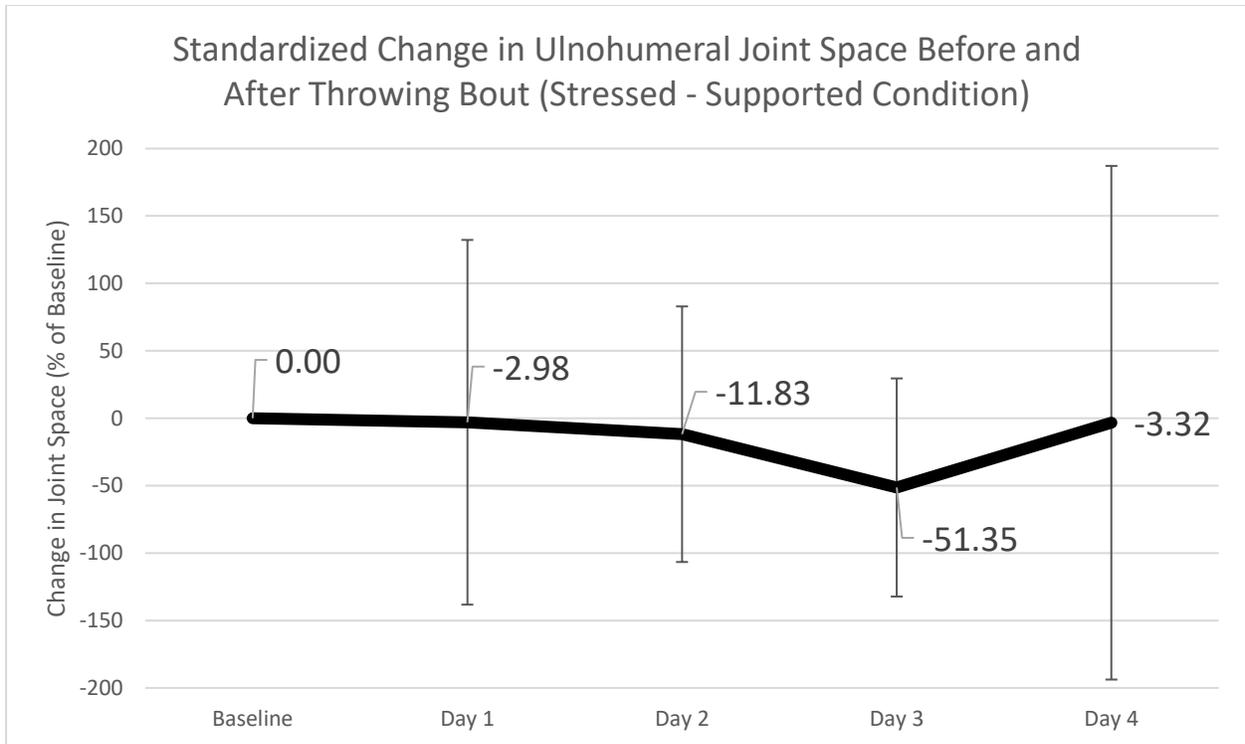


Figure 12: The mean difference between ulnohumeral gap space in the supported condition and the stressed condition reported as percentage of baseline. Mean is presented with standard deviation bars.

Figures 13 and 14 show individual joint space change across the study timeframe. With a single glance, this appears to be a very noisy dataset, with seemingly random fluctuations within subjects. There are no clear outliers in this measurement, however some discrepancies with current literature are prevalent. This will be further discussed in the following chapter.

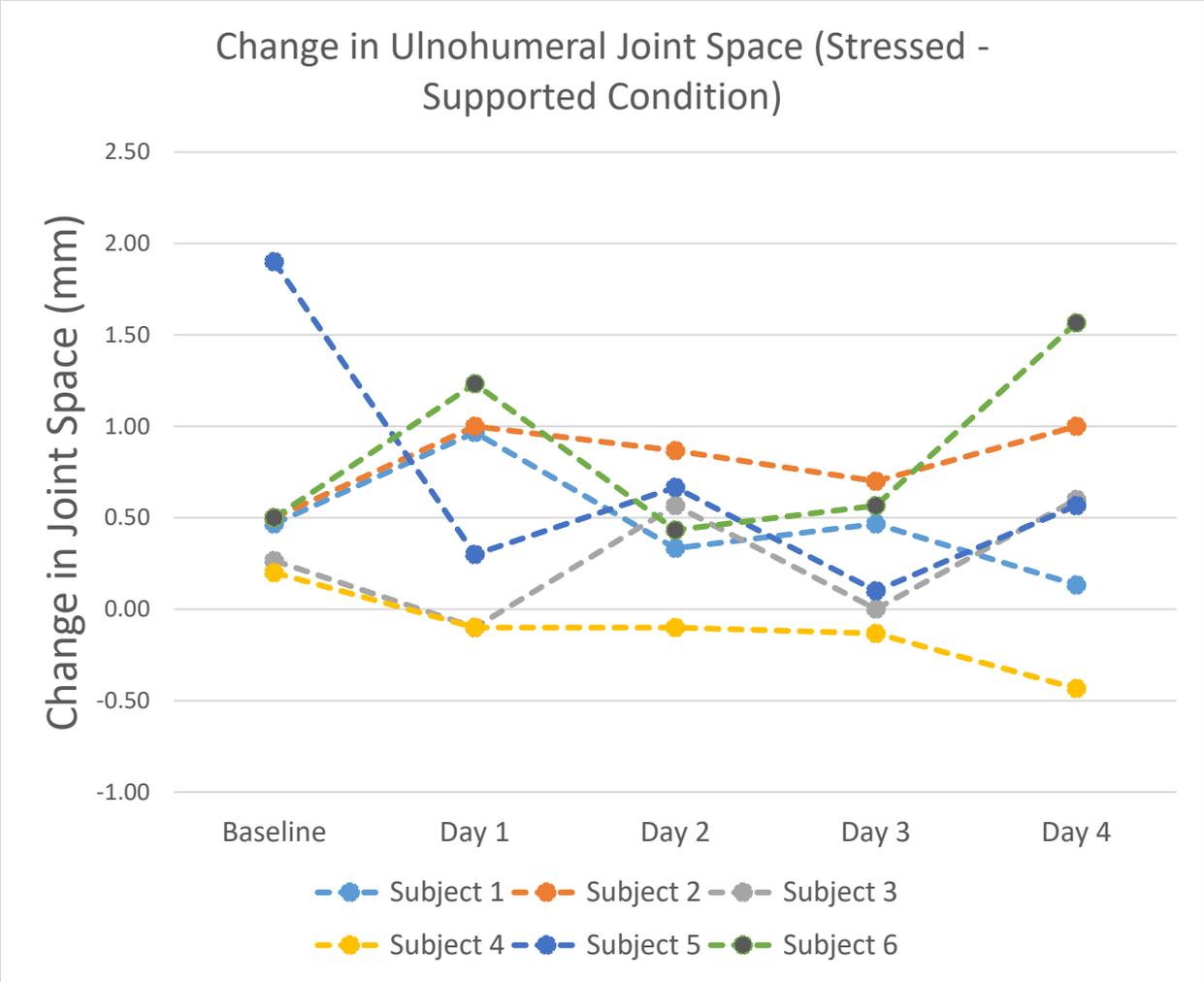


Figure 13: Individual differences in ulnohumeral gap space between stressed and supported conditions, before and after the pitching bout.

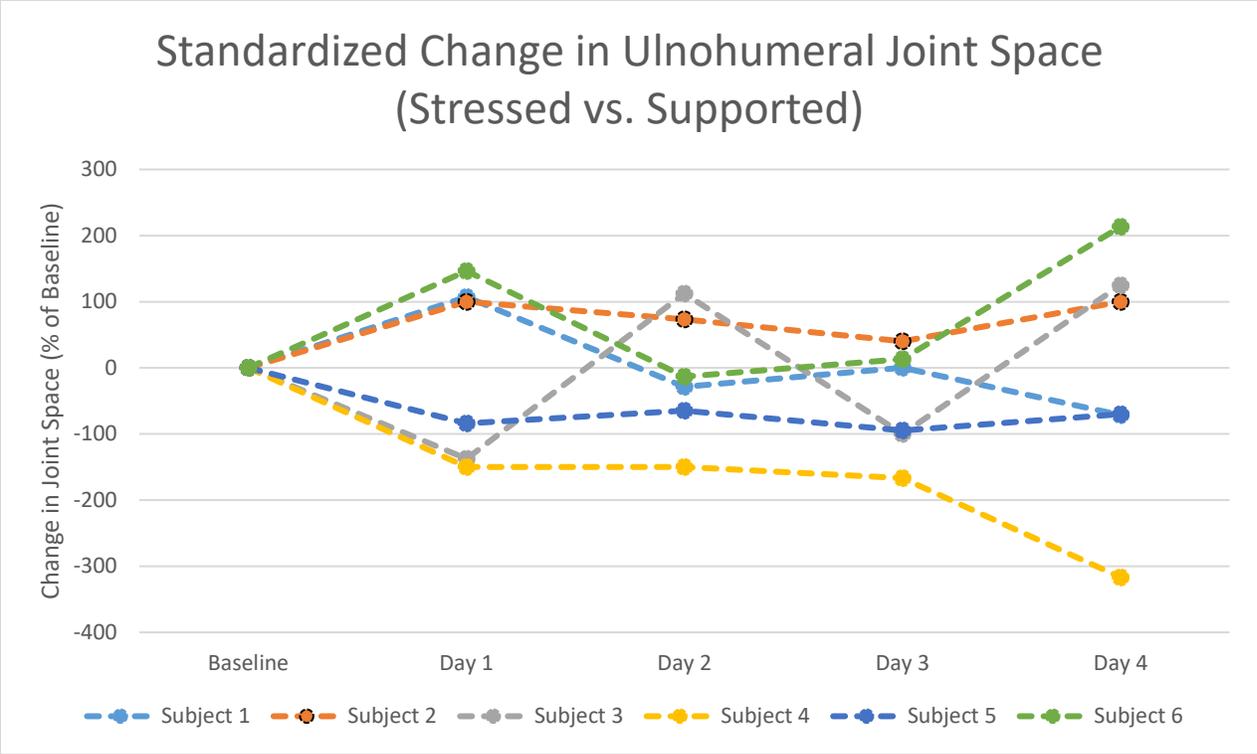


Figure 14: Individual differences in ulnohumeral gap space between stressed and supported conditions, before and after the pitching bout. Values reported as percentage of baseline.

Figures 15 and 16 show individual joint space measurements in both stressed and supported conditions. Most values stay relatively close to baseline, with the exception of subject 5 under the stressed condition. These are the values that are subtracted from each other to calculate difference in ulnohumeral gap space.

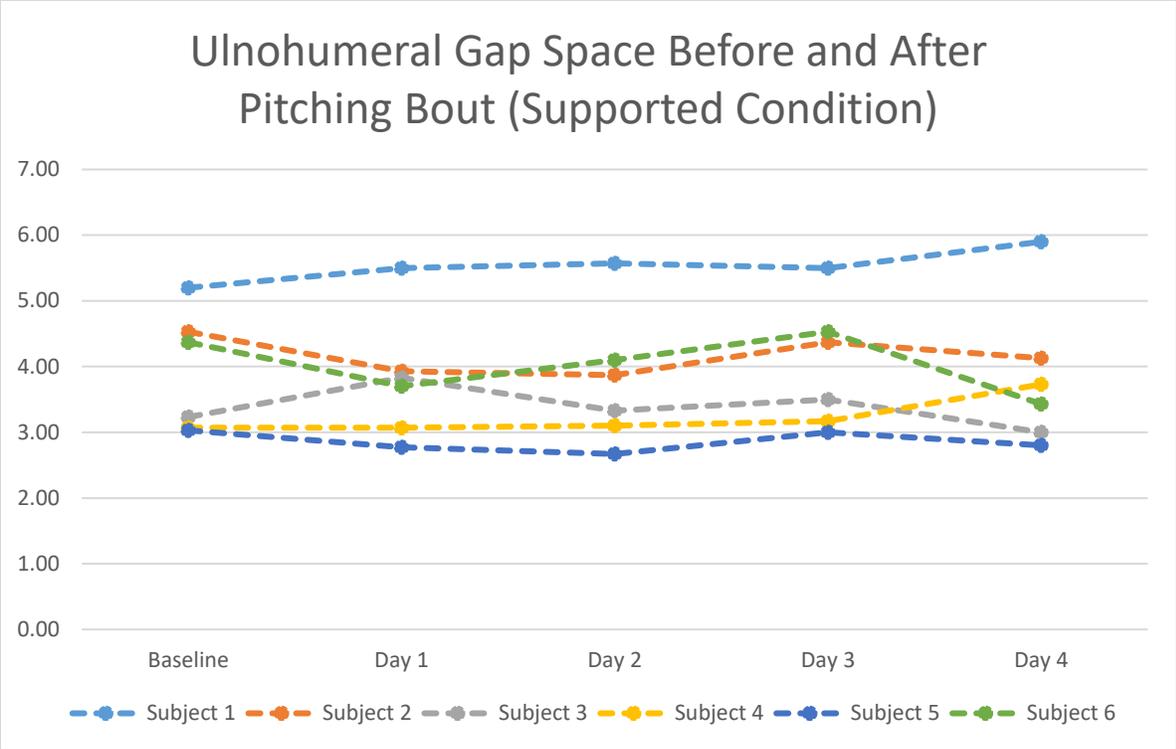


Figure 15: Ulnohumeral gap space in the supported condition.

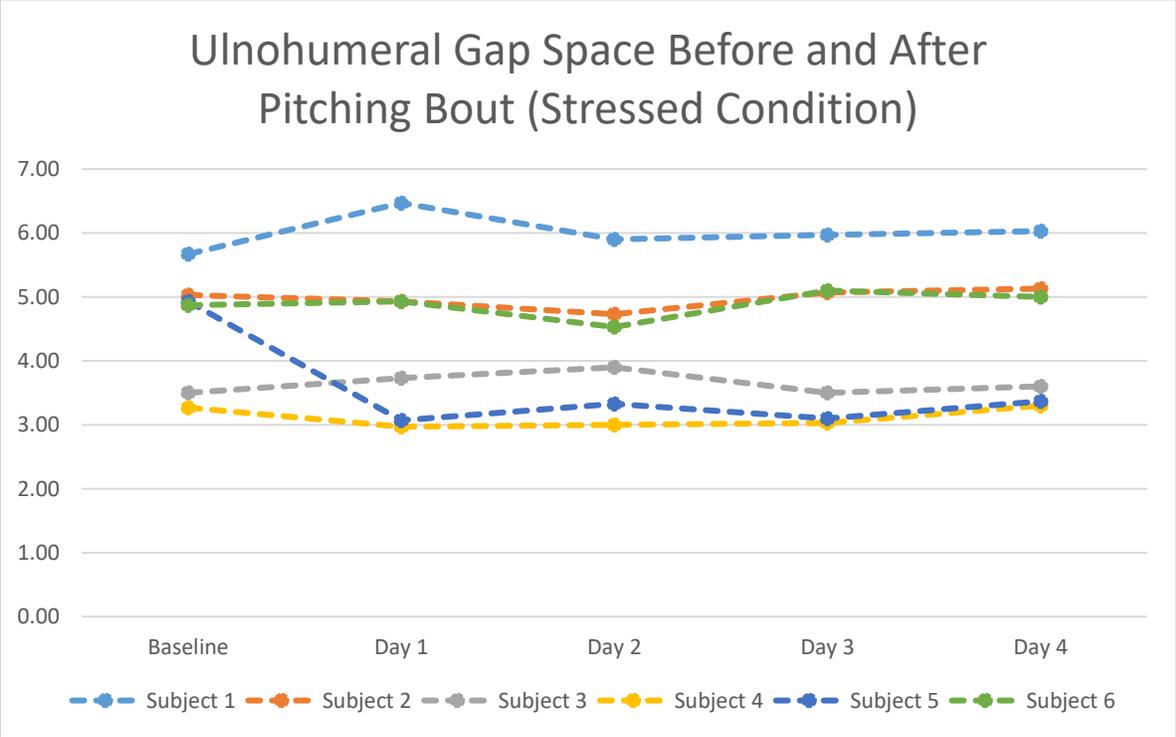


Figure 16: Ulnohumeral gap space in the stressed condition.

A regression of ulnohumeral gap difference and stiffness values was performed to see how stiffness and joint space are connected. Theoretically, as stiffness increases, the difference would decrease, providing a negative trend. The R^2 value of 0.020 shows there is no correlation between these two variables (Figure 17).

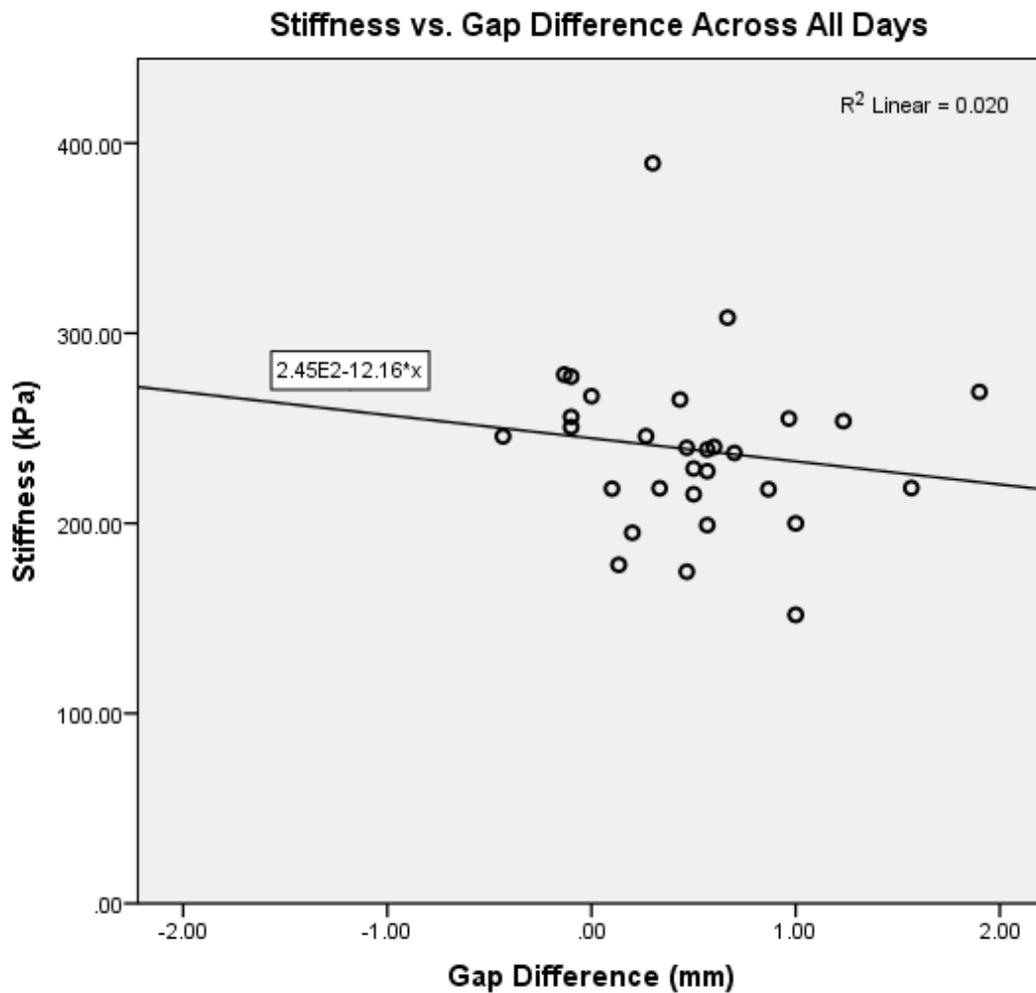


Figure 17: Linear regression of the relationship between stiffness and gap difference. The regression was not significant at the 0.05 level.

Elbow Circumference

Elbow circumference was taken on each day of the study protocol, to measure if any swelling occurred throughout the recovery period (Table 14). Fluctuations in circumference are measured in percentages of baseline. No significant fluctuations occurred, indicating no acute injuries were sustained during the pitching bouts.

TABLE 14
Change in Elbow Circumference from Baseline (% of Baseline)

Subject	Day 1	Day 2	Day 3	Day 4
Subject 1	1.75	0.88	0.88	1.75
Subject 2	0.79	1.59	0.79	-0.79
Subject 3	-2.56	-1.71	0.00	0.85
Subject 4	-1.61	0.81	1.61	0.00
Subject 5	1.49	1.49	0.00	0.00
Subject 6	0.00	0.00	1.72	3.45

Pitch Velocity

Pitch count, type, and velocity was recorded for the 6 participants throwing bouts (Table 15). Fastball pitch percent refers to the percentage of total pitches that were fastballs. The remainder was simply designated as “off-speed”. Pitch type was not differentiated in any other way beside fast-ball and off-speed. All participants met the requirements of pitching within 10% of their estimated fastball pitch speed, therefore no pitching bouts had to be repeated.

TABLE 15
Pitching Bout Data

	Total Pitch Count	Max Fastball Velocity	Mean Fastball Velocity	Fastball Pitch Percent
Subject 1	50	76	72.2	68%
Subject 2	50	82	76.4	50%
Subject 3	60	86	81.9	52%
Subject 4	61	77	73.5	75%
Subject 5	52	83	79.8	78%
Subject 6	60	75	71.3	70%

DISCUSSION

Despite the increasing rates of UCL injuries in both youth and professional levels of baseball pitchers, we currently lack an objective measure that correlates with arm health. Cross-sectional studies have observed UCL thickness to increase with age and pitching volume, however this adaptation is seen in both symptomatic and asymptomatic pitchers. Longitudinal studies have seen increases in elbow joint laxity with valgus stress, but again, no differences in healthy players and those who later would incur injury. Shearwave elastography allows researchers further insight into soft tissue health by calculating the materials Young's modulus, which may change as the ligament undergoes acute or chronic microtrauma. The current study evaluated the change in stiffness of the UCL before and after a single pitching bout, and throughout the following 4 days of rest to identify directional patterns. In addition to UCL stiffness, ulnohumeral joint space width was measured in both stressed and supported conditions to calculate the change in joint laxity throughout the study. Participants also completed the Kerlan-Jobe Orthopedic Clinic Shoulder and Elbow Health Questionnaire.

UCL Stiffness

No significant differences in stiffness were found between study days, although there seems to be a general pattern in the results, with the exception of one individual (to be further discussed shortly). Mean stiffness increased slightly on the first day after the pitching bout, then lowered back down to baseline by Day 3 of the rest phase (Figures 5 & 6), all at insignificant levels. This was somewhat along the lines of what we expected to see. We

hypothesized an increase in ligament stiffness after the pitching bout, and the return to baseline within the following four days of rest. This return to baseline suggests that the 4 days of rest allotted to starting pitchers after a game may be adequate time for proper tissue repair. With such a small sample size, statistical significance was unlikely from the start. The small sample size was compounded with high variability between different subject's baseline stiffness values, as well as the high degree of variance within participants. One participant in particular experienced drastic changes in stiffness throughout the study timeframe, with a range of 171kPa (elastograms for Participant 5 shown in Appendix D).

Rest Day 1 saw the greatest variability between the six participants stiffness scores. Five of the six pitchers experienced increased UCL stiffness on the day immediately after the pitching bout, while one pitcher's stiffness sharply declined (Figures 5 & 6). This may mean that people respond differently to acute stress, or there are external factors affecting the outlier, such as arm health or amount of tensile load applied to the ligament throughout the throwing session. The degree of change observed across pitchers varied highly, and it can be difficult to draw the line between daily fluctuations, and real changes attributed to the pitching bout. Previous reliability data has reported within-participant standard deviations of 25.7kPa (unpublished data), meaning that changes of that magnitude may simply be due to measurement error or normal fluctuations of ligament material properties. 3 of the participants of this study experienced changes in stiffness of less 25.7kPa (1 SD of reliability data), while the other 3 participants experienced change of approximately 2.5 standard deviations or higher. The difference of magnitude in stiffness change suggests that some of our pitchers did not

accumulate significant microtrauma throughout the pitching bout to illicit changes in material properties.

The difference in stiffness we saw was similar to the difference that Wu et al. recorded in the coracohumeral ligament in patients with frozen shoulder symptoms⁶⁴. However, because this change is approximately equal to one standard deviation of our reliability study, it can't be said for sure this was a true change. Their research group found that symptomatic shoulders were 31.5kPa stiffer than the healthy group (234.8; 203.3). The current study saw a mean increase of 30.67kPa above baseline after the pitching bout (Table 6). Given the lack of literature on elastography in ligamentous applications, it is certainly interesting to see these values agree. The largest difference in stiffness between study days was Day 1 and Day 4 of the rest period. Day 1 had the highest mean stiffness, and Day 4 dropped below baseline by 4.8%.

Of all participants, Participant 5 saw the largest change in stiffness after the pitching bout, with an increase of 120kPa. This is interesting, because of several important differences between Participant 5 and the rest of the cohort. He was the only player to throw in an official game rather than a bullpen, which undoubtedly increased his effort, and likely his total throwing load. Warm-up pitches were not included in any of the pitch counts for the current study, and due to the break between innings, Participant 5 likely had many more warm-up throws than the other players. He was also the only participant in the study to report zero arm problems (100.0 cumulative KJOC score). And finally, he was one of the fastest throwing pitchers we observed, with a mean fastball speed of 79.8mph, and a max fastball speed of 83mph. The combination of higher speeds, increased throwing load, increased effort, and great arm health likely accounted for this extreme change in stiffness.

Although insignificant changes in stiffness were found in this study, a pattern is visible in the mean stiffness before and after the pitching bout (Figures 7 & 8). The question becomes, what could potentially cause a change in stiffness in such a short time period? Ligaments primarily consist of type I collagen; however, this is an unlikely source of the change in material properties. Changes in stiffness attributed by a significant loss of collagen would only be likely in the case of an acute injury, while the participants of the current study are merely experiencing mild microtrauma associated with the pitching motion^{33,58}.

Perhaps a more plausible reason for this increase in stiffness after ligament microtrauma is local inflammation of the strained tissue. Given the well documented rise in UCL thickness over the course of a baseball pitcher's career^{5,11,42}, one can surmise there is a long-term uptick in collagen deposition that is responsible for this increased cross-sectional area. These are gradual changes which occur over years of play and are directed by a host of intracellular events. Influx of monocytes, macrophages, and cytokines work to repair severed fibers and proliferate new cells. It is possible that as these cells that are associated with the healing phase enter the ligament, interstitial and/or intracellular pressure rises, with a concurrent rise in ligament stiffness. We believe this might be an adaptive response in baseball pitchers. The differences in ligament response to exercise between trained and untrained individuals is necessary to draw clear conclusions.

Ulnohumeral Joint Space

No significant changes were observed in the difference between ulnohumeral joint space while supported, and joint space with valgus stress applied (Table 11). Furthermore, the pattern of change that was observed did not correlate with ligament stiffness. If the difference between the two gap space measurements decreases from one day to another, this would suggest the ligament restricting valgus motion (the anterior band of the UCL) is getting stiffer. Theoretically, these two measurements should have a negative correlation, but our results did not point to this conclusion (Figure 17).

One potential explanation for the lack of change seen in gap space is involuntary muscle guarding. In two of the subjects (subjects 3 and 4), we even observed a smaller gap space under the supported condition, than under the stressed condition. This is theoretically impossible and is a red flag that an error occurred during data collection in these people. The wooden splint used in the study holds the arm in an externally rotated position with 30 degrees of elbow flexion (to place the responsibility of valgus resistance mostly on the UCL). This device assists in maintaining proper position of subject's arm but does not act to minimize muscle guarding. Subjects were verbally cued to relax, and let the weight hang loosely in the hand without gripping too hard.

If participants 3 and 4 were subconsciously activating the musculature around the elbow to resist valgus motion, the joint space measurement would underestimate the actual laxity of the joint. When comparing the joint space of these two pitchers to results commonly found in baseball literature, some differences arise. Mean ulnohumeral joint space with stress has been found to vary between 4.2mm and 5.9mm^{5,48,59} in baseball pitchers of similar age. The

difference in joint space between the supported and stressed conditions has been repeatedly reported at greater than 1mm, with most researchers reporting the difference at approximately 1.4mm. The stiffness measurements of participants 3 and 4 may also have been affected by any muscle guarding that took place, although likely to a lesser degree than joint space. As long as enough stress was still applied to the UCL to remove any collagen crimping, the measurements would still be taken within the linear region of the stress-strain curve, and should still produce similar results. Given the fact that neither subjects 3 or 4 are extreme outliers in stiffness, it appears that sufficient tension was produced along the UCL.

By no means is this definitive evidence that participants 3 and 4 were subconsciously muscle guarding. Both participants had joint space measurements that fell within 1.5 standard deviations of our sample mean, and studies have reported joint space ranges as low as 1.6mm⁴⁸. It is the combination of small baseline joint space with stress (when compared to previously reported samples), and small differences between the rested and stressed conditions. If these two scenarios were indeed the case, one might suspect that they simply had very low joint laxity, and the stiffness of their UCL was the cause of this minimal change in gap space. On the contrary, these participants had relatively average ligament stiffness, both falling within 1 standard deviation from the mean. Based on the findings of the current study, it appears that difference in ulnohumeral joint space may not be sensitive enough of a measurement to see changes on a day to day basis, with regards to pitcher health.

KJOC Scores

The mean KJOC score of the six participants was 81.85, with a range of 60.2-100 (Table 5). Four of the participants categorized themselves as “playing without any arm trouble”, while two pitchers described their status as “playing, but with arm trouble”. When these values are compared to those of a typical group of asymptomatic pitchers, questions are raised about the overall health of this sample. Previous work by Kraeutler et al. has suggested that a KJOC score below 90 could be a potential cause for concern³⁴. They administered the questionnaire to 44 professional baseball pitchers and reported a mean KJOC score of 94.82. Of note, the AAA players within the study had significantly higher KJOC scores than the AA and A level players, revealing that the average pitcher at higher levels may be less symptomatic. Other studies have corroborated this conclusion, while drawing from populations of more similar age and experience to the current study. Alberta et al. gave the questionnaire to a mix of collegiate and professional overhead athletes with a mean age of 23.7. The mean score was 96.22, with a median of 99.3, in the 119 athletes with no history of injury.

Considering that 4 of our six participants scored less than 90 on the KJOC, it is possible that this small sample size was particularly unhealthy. Being at the club level, some of our participants may not take all recommended measures to maintain arm health (such as icing, resting the appropriate amount of time between bullpens etc.), which is why we see such variability in the KJOC score. Another potential reason is that we are seeing more honest answers from the players compared to other studies. Although research was done with the coaching staff’s permission, they did not supervise or monitor the results of the study. Players

may have felt more comfortable admitting to arm pain, compared to a scenario where they knew coaches might find out, and limit their playing time.

Outliers

Within this group of relatively low KJOC scores, there was one player who's arm health stood out. Subject 2 self-reported a 60.2 in the 10-question cumulative portion of the KJOC, and described himself as "playing, but with arm trouble". Some of the arm issues he has the most trouble with include control of pitch (4.5), weakness/fatigue (3.5), and elbow pain (2.0, mild pain at rest). Interestingly, this same player is the only participant to see a drop in UCL stiffness on the day following the pitching bout. He experienced a -29.5% change in stiffness after pitching, while the other 5 participants showed a mean increase of 21.2%. When looking at all 6 subjects, the effect size of the change in stiffness between Day 1 and Day 4 (representing change in stiffness during recovery) is small (ES = 0.37). When Participant 2 is removed, the effect size becomes medium (ES = 0.56). The effect size of the change in stiffness between Baseline and Day 1 in all subjects, and when excluding Participant 2 were both classified as small (ES = 0.26 and 0.47, respectively). Given the extreme nature of this participant's arm health and stiffness response, we have reason to believe this player's arm health is worse than the rest of the sample and is exhibiting different repair processes which result in the lower ligament stiffness.

Due to the fact that Subject 2's stiffness values returned to approximately baseline the following day, massive collagen damage is not a viable possibility. Like the healthy subjects, the

reason for material property change is more likely due to histological fluctuations than gross morphological change. Due to a gap in the literature, changes in ligament histology after exercise similar to that experienced in a baseball pitch is unknown. What we may be observing is some change in proteoglycan content which is responsible for this reduced stiffness. Lower proteoglycan concentrations would theoretically decrease the water content of the ligament, and as a result, the stiffness as well. More research in exercise-induced histological changes of ligament tissue is needed to explore these possibilities.

Although we may not know the precise mechanisms of this drop in stiffness, other connective tissues have shown similar patterns. As previously discussed, the stiffness of healthy tendons increases with exercise⁵⁷. This rise agrees with the pattern of ligament stiffness we observed acutely after the pitching bout in our healthy pitchers. Stiffness only declined in our least healthy subject, suggesting his arm may be in an entirely different state of health than the rest of the sample. Looking at past literature, we see that the stiffness of pathologic tendon is significantly lower than matched controls⁴. Additionally, those with tendinopathy display an increased CSA compared to control, as we know injured ligament does²⁵. Theoretically, there is some point where the demands placed on the UCL are too great for it to withstand, and tissue integrity declines before presenting symptoms. Elastography may be able to give insight as to the direction of the health of the ligament, based on the acute response to loading of the tissue's material properties.

Elbow Circumference

No significant change in elbow joint circumference was measured. Interobserver variation for mid-arm circumference has been reported to be 4.7%³⁰, which is higher than any change in circumference we observed throughout the study. If we had seen significant swelling, that could have been due to an acute injury the player experienced during the pitching bout. The absence of notable swelling suggests that the observed pitching bout was within the subjects physical limitations, and we are not witnessing changes in ligament stiffness due to acute injury.

Limitations

There were a few limitations to this study, the first of which being a small sample size. With only 6 participants, the changes in ligament stiffness we observed did not reach statistical significance. Study recruitment was limited to a relatively small population, and by focusing on one specific club baseball team, we were able to recruit a more homogenous subject pool with respect to age, experience, and skill level.

Second, there was some variability in the pitching bouts which each participant performed in the study. All pitchers met the inclusion criteria of at least 50 pitches, but this number excluded warm-ups, which were uncontrolled. Pitch velocity, pitch type, and exact pitch count were also uncontrolled, but were recorded (Table 15). All pitchers did throw within 10% of their estimated fastball speed max, which was used as a rating of exertion.

Lastly, with the high degree of variability in stiffness change observed after the pitching bout, it is possible the throwing load we used was not enough to illicit changes in stiffness in some of the pitchers. Two of the six pitchers saw changes of less than 7% of baseline, while others changed over 40%. Current level of conditioning may have been a factor in this respect. While 50 pitches may have been close to some of the pitcher's standard workload, a higher volume of work may be necessary for the more experienced or better conditioned pitchers. Pitching may have a dose-response effect on changes in ligament stiffness, with larger changes in stiffness seen with a greater volume of pitching.

Conclusions

While we did not reach statistical significance in the changes of stiffness we observed, a qualitative pattern is visible. Ligament stiffness appears to increase slightly after the acute microtrauma experienced by the UCL during a pitching bout in healthy collegiate baseball players. This change in material properties of the ligament has yet to be linked to soft tissue health, but the potential application of a quantitative, non-invasive measure of ligament health is vast. With an imaging session that ranges from 5-10 minutes for a trained sonographer, this technology could benefit clinical and athletic settings in providing efficient and objective evaluation of ligament health. The difficulty in identifying this correlation lies in the necessary scope of the potential study. A study capable of establishing a statistically significant link between health and ligament stiffness would likely take hundreds of participants, over many years. Cicotti et al. amassed 368 pitchers over a 10-year period. 12 of them incurred a UCL injury, however this number was found to be insignificant with regard to the factors they were

observing; UCL thickness and ulnohumeral joint space. A study of similar magnitude is likely necessary to demonstrate a connection between the material properties of a ligament and its health.

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APPENDIX A: DEMOGRAPHICS AND THROWING LOAD QUESTIONNAIRE

Participant: _____

Initial Visit:

Date_____

Age: _____ years

Height: _____ cm

Weight: _____ kg

Last day pitched? _____

Informed Consent Complete: _____

KJOC Complete: _____

Elbow Circumference: _____

Day 1:

Date_____

How many pitches did you throw? _____

Did you experience any abnormal symptoms after pitching? **Y / N**

Warm-up Intensity: _____

Resistance Training? Y/N

Elbow Circumference: _____

Day 2:

Date_____

Have you pitched since your previous session? **Y / N**

Elbow Circumference: _____

Day 3:

Date_____

Have you pitched since your previous session? **Y / N**

Elbow Circumference: _____

Day 4:

Date_____

Have you pitched since your previous session? **Y / N**

Elbow Circumference: _____

APPENDIX B: KJOC QUESTIONNAIRE

Kerlan-Jobe Orthopaedic Clinic Shoulder & Elbow Score

Name _____ Age _____ Sex _____ Dominant Hand (R) _____ (L) _____ (Ambidextrous)
 _____ Date of Examination _____ Sport _____ Position _____ Years Played _____

Please answer the following questions related to your history of injuries to **YOUR ARM ONLY**:

- | | YES | NO |
|---|--------------------------|--------------------------|
| 1. Is your arm currently injured? | <input type="checkbox"/> | <input type="checkbox"/> |
| 2. Are you currently active in your sport? | <input type="checkbox"/> | <input type="checkbox"/> |
| 3. Have you missed game or practice time in the last year due to an injury to your shoulder or elbow? | <input type="checkbox"/> | <input type="checkbox"/> |
| 4. Have you been diagnosed with an injury to your shoulder or elbow other than a strain or sprain?
If yes, what was the diagnosis? _____ | <input type="checkbox"/> | <input type="checkbox"/> |
| 5. Have you received treatment for an injury to your shoulder or elbow?
If yes, what was the treatment? (Check all that apply)
<input type="checkbox"/> Rest <input type="checkbox"/> Therapy <input type="checkbox"/> Surgery (please describe): _____ | <input type="checkbox"/> | <input type="checkbox"/> |

Please describe your level of competition in your current sport:
 (Use Professional Major League, Professional Minor League, Intercollegiate, High School as the choices)

6. What is the highest level of competition you've participated at? _____
7. What is your current level of competition? _____
8. If your current level of competition is not the same as your highest level, do you feel it is due to an injury to your arm? YES NO

Please check the **ONE category only** that best describes your current status:
 Playing without any arm trouble Playing, but with arm trouble
 Not playing due to arm trouble

Instructions to athletes:

The following questions concern your physical functioning during game and practice conditions. Unless otherwise specified, all questions relate to your **shoulder or elbow**. Please answer with an **X** along the horizontal line that corresponds to your current level.

1. How difficult is it for you to get loose or warm prior to competition or practice?



2. How much pain do you experience in your shoulder or elbow?



3. How much weakness and/or fatigue (ie, loss of strength) do you experience in your shoulder or elbow?



4. How unstable does your shoulder or elbow feel during competition?



5. How much have arm problems affected your relationship with your coaches, management, and agents?



The following questions refer to your level of competition in your sport. Please answer with an X along the horizontal line that corresponds to your current level.

6. How much have you had to change your throwing motion, serve, stroke, etc. due to your arm?



7. How much has your velocity and/or power suffered due to your arm?



8. What limitation do you have in endurance in competition due to your arm?



9. How much has your control (of pitches, serves, strokes, etc.) suffered due to your arm?



10. How much do you feel your arm affects your current level of competition in your sport (ie, is your arm holding you back from being at your full potential)?



APPENDIX C: INFORMED CONSENT DOCUMENT

East Carolina University



Informed Consent to Participate in Research

Information to consider before taking part in research that has no more than minimal risk.

Title of Research Study: Shearwave Elastography: A prospective study on short term changes in UCL health of college baseball pitchers

Principal Investigator: Zac Domire

Institution/Department or Division: Kinesiology

Address: 332 Ward Sports Medicine Building, East Carolina University

Telephone #: 252-737-4616

Researchers at East Carolina University (ECU) study problems in society, health problems, environmental problems, behavior problems and the human condition. Our goal is to try to find ways to improve the lives of you and others. To do this, we need the help of volunteers who are willing to take part in research.

Why is this research being done?

The purpose of this research is to examine short term changes in the elastic properties of the ulnar collateral ligament of collegiate baseball pitchers between starting pitching bouts, and to determine if relationships exist between UCL stiffness and elbow pain or soreness. The decision to take part in this research is yours to make. By doing this research, we hope to learn more about the material properties of the ulnar collateral ligament in collegiate baseball pitchers as they recover between starting pitching bouts. Hopefully this work can be used in the future to optimize recovery programs and help prevent elbow injuries.

Why am I being invited to take part in this research?

You are being invited to take part in this research because you meet the inclusion criteria and appear to be free of contraindications to participating in this study. Inclusion criteria for this study are: 18-25 years old and a competitive baseball pitcher, currently training with a team. If you volunteer to take part in this research, you will be one of approximately 20 people to do so.

Are there reasons I should not take part in this research?

I understand that I should not take part in this research if I am not between the ages of 18 and 25 years old or if I am not a competitive baseball pitcher.

What other choices do I have if I do not take part in this research?

You can choose not to participate.

Where is the research going to take place and how long will it last?

The research procedures will be conducted in the Biomechanics Laboratory, room 332 Ward Sports Medicine Building at ECU. You will need to come to the Biomechanics Laboratory one day prior to the observed pitching bout, as well as the 4 days following the pitching bout. Each research session will last approximately 20 minutes. The total amount of time you will be asked to volunteer for this study is 3 hours throughout the remainder of the 2017 season.

Page 1 of 3

Consent Version # or Date: _____

What will I be asked to do?

You are being asked to do the following:

1. Have the stiffness of your throwing elbow measured using ultrasound. This is similar to the device used to monitor the fetus in pregnant women, therefore totally harmless.
2. Complete two short questionnaires on your initial visit, and one questionnaire (identical to one of the two administered on the initial visit) on each follow-up session regarding the amount of throwing you have been doing and your perception of any stiffness or pain in your elbow.

What possible harms or discomforts might I experience if I take part in the research?

It has been determined that the risks associated with this research are no more than what you would experience in everyday life. You should not experience any discomfort from any aspect of this study. If you do experience discomfort, please inform the study staff.

What are the possible benefits I may experience from taking part in this research?

We do not know if you will get any benefits by taking part in this study. This research might help us learn more about short term changes that can take place in ligament tissue. There may be no personal benefit from your participation but the information gained by doing this research may help others in the future.

Will I be paid for taking part in this research?

We will not be able to pay you for the time you volunteer while being in this study.

What will it cost me to take part in this research?

It will not cost you any money to be part of the research.

Who will know that I took part in this research and learn personal information about me?

To do this research, ECU and the people listed below may know that you took part in this research and may see information about you. With your permission, these people may use your private information to do this research:

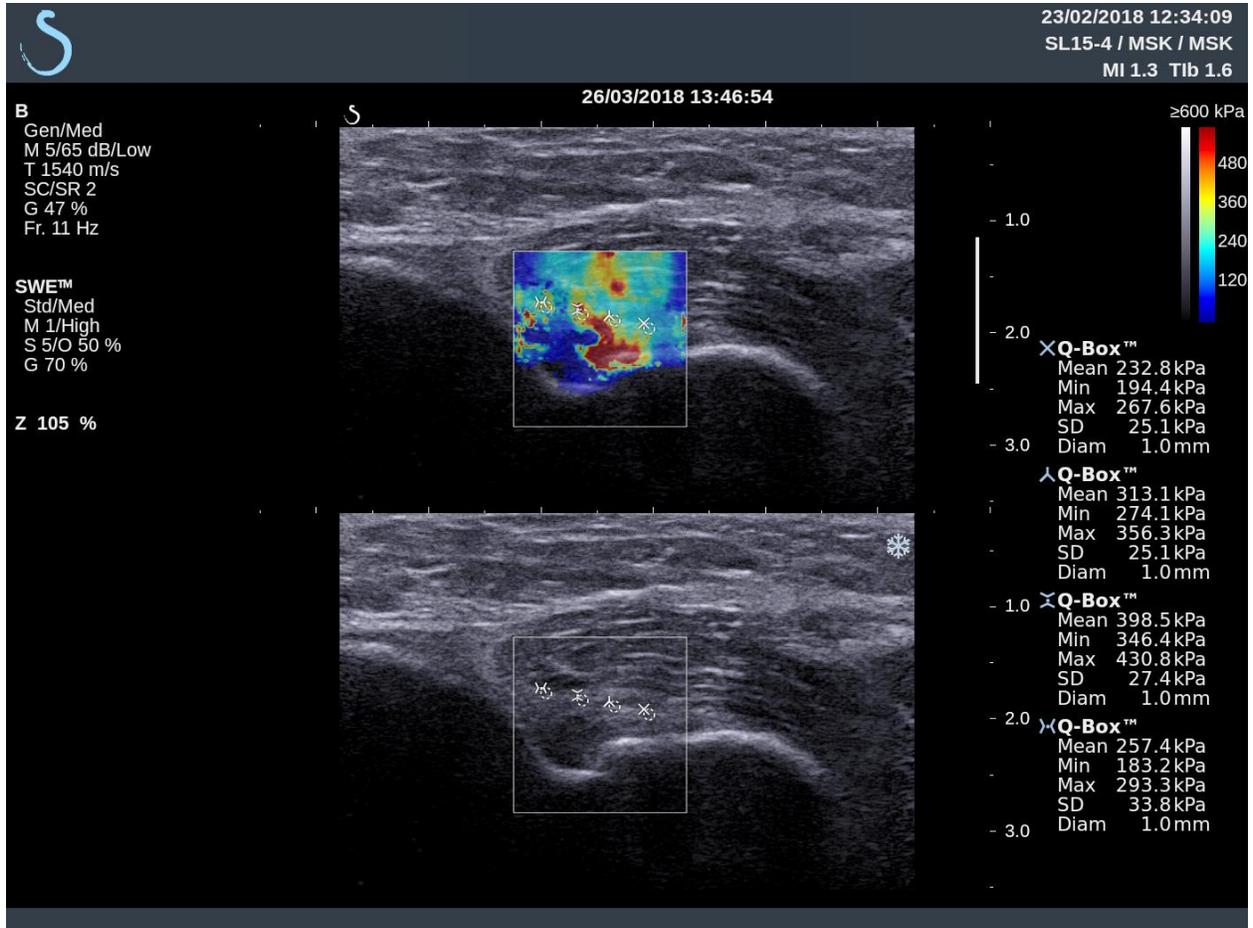
- Any agency of the federal, state, or local government that regulates human research. This includes the Department of Health and Human Services (DHHS), the North Carolina Department of Health, and the Office for Human Research Protections.
- The University & Medical Center Institutional Review Board (UMCIRB) and its staff, who have responsibility for overseeing your welfare during this research, and other ECU staff who oversee this research.
- Dr. Zac Domire, the primary investigator and faculty supervisor, and sub-investigators for this study.

How will you keep the information you collect about me secure? How long will you keep it?

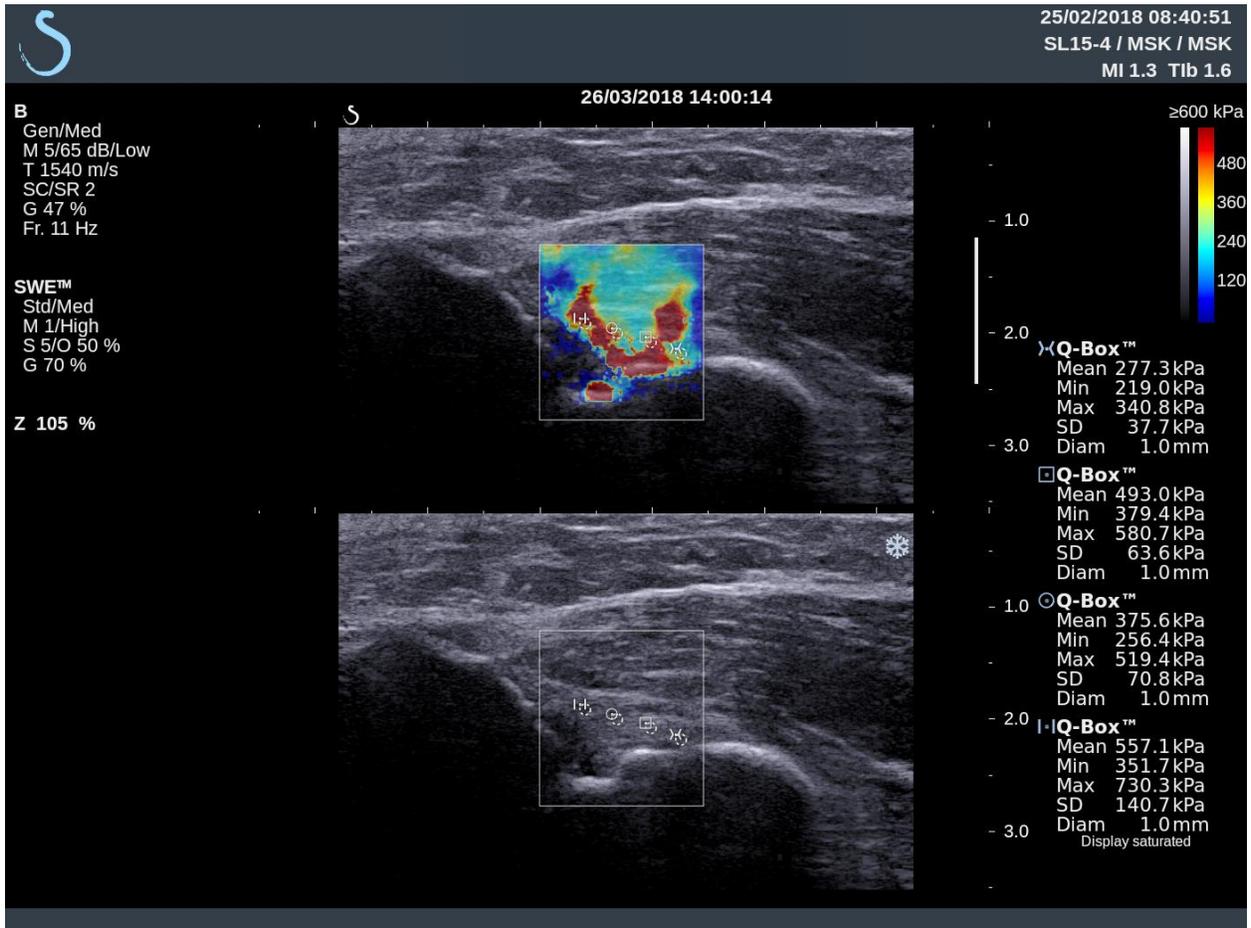
Data files will be kept for 5 years after the study is completed. The investigators will keep your personal data in strict confidence by having your data coded. Instead of your name, you will be identified in the data records with an identity number. Your name and code number will not be identified in any subsequent report or publication. The main investigator and the research students will be the only persons who know the code associated with your name and this code as well as your data will be kept in strict confidence. The computer file that matches your name with the ID number will be encrypted and the main investigators will be the only staff that knows the password to this file. The data will be used for research purposes.

APPENDIX D: ELASTOGRAMS OF SUBJECT 5

Subject 5 Baseline Elastogram (before pitching bout)



Subject 5 Day 1 Elastoram (following pitching bout)



APPENDIX E: IRB APPROVAL LETTER



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**
www.ecu.edu/ORIC/irb

Notification of Initial Approval: Expedited

From: Biomedical IRB
To: [Zachary Domire](#)
CC: [Zachary Domire](#)
Date: 10/25/2017
Re: [UMCIRB 16-002371](#)
Shearwave Elastography: A prospective study on short term changes in UCL health of college baseball pitchers

I am pleased to inform you that your Expedited Application was approved. Approval of the study and any consent form(s) is for the period of 10/24/2017 to 10/23/2018. The research study is eligible for review under expedited category #4,7. The Chairperson (or designee) deemed this study no more than minimal risk.

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 continuing review/closure application to the UMCIRB prior to the date of study expiration. 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:

Name	Description
KJOC	Surveys and Questionnaires
Shearwave UCL Informed Consent Fall 2017	Consent Forms
Short Term Changes in Pitching Elbow Health Protocol	Study Protocol or Grant Application
Throwing Load Questionnaire	Surveys and Questionnaires

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

