CHANGES IN THE STRUCTURAL PROPERTIES OF THE UCL IN COLLEGIATE BASEBALL PITCHERS

by

Christopher James Curran

July 2017

Director of Thesis: Patrick Rider

Major Department: Kinesiology

Abstract: Perhaps the most serious injury for a baseball pitcher is a full tear of the ulnar collateral ligament (UCL) in their throwing arm. Full tears of the UCL require surgical reconstruction if the athlete hopes to return to throwing at the same level. The UCL, which is the primary stabilizer of the medial elbow, is exposed to high valgus stresses during the baseball pitching motion. Very few studies have performed pre- and post-season ultrasound imaging to measure the properties of the UCL, and none have performed mid-season imaging at regular intervals in order to track changes in the UCL. There is a need for better understanding of the changes which take place in the UCL of baseball pitchers prior to suffering a significant injury to the UCL in their throwing arm in order to help decrease the alarming rate of UCL tears in baseball pitchers. The primary purpose of this study was to examine changes in the structural properties of the UCL and medial elbow in NCAA Division I collegiate baseball pitchers over the course of a season. The secondary purpose of this research was to determine if relationships exist between recent throwing load, upper body resistance training, and perceived medial elbow stiffness with any observed changes in the structural properties of the UCL and medial elbow. To evaluate these purposes, we performed biweekly ultrasound imaging on 12 healthy collegiate baseball pitchers throughout the course of a collegiate baseball season. Four structural properties of the UCL were measured for each imaging session, including the length and thickness of the ligament, UCL space, and the ulnohumeral gap.

Participants completed questionnaires reporting their pitching and resistance training workload, as well as perceived elbow stiffness variables in order to evaluate any potential correlations between changes in the UCL and these self-reported metrics. The results of the imaging sessions displayed significant bilateral differences in UCL properties at the pre- and post-season timepoints, and significant changes in the properties of the UCL in the participants' throwing arms compared to the pre-season imaging session. Our results did not show any significant changes between biweekly imaging sessions for any of the structural properties of the UCL in the throwing arms of our participants. The results of this study demonstrate the continued need for a new method of measuring the health of a baseball pitcher's throwing arm, specifically the UCL, in order to determine when throughout a season, and the factors that lead to, a pitcher being at an elevated risk of tearing the UCL. Such information would be helpful to the coaching, training, and medical staffs involved with high level baseball, who attempt to aid pitchers in remaining healthy and increasing their pitching performance.

Changes in the Structural Properties of the UCL in Collegiate Baseball Pitchers

A Thesis

Presented to the Faculty of the Department of Kinesiology

East Carolina University

In Partial Fulfillment of the Requirements for the Degree

The Masters of Science in Kinesiology,

Biomechanics Concentration

by

Christopher James Curran, CSCS

July 2017

CHANGES IN THE STRUCTURAL PROPERTIES OF THE UCL IN COLLEGIATE BASEBALL PITCHERS

By

Christopher James Curran

APPROVED BY:

DIRECTOR OF THESIS: ____
Patrick Rider, MS, MS

COMMITTEE MEMBER: ____
Zachary Domire, PhD

COMMITTEE MEMBER: ____
Anthony Kulas, PhD

CHAIR OF THE DEPARTMENT
OF KINESIOLOGY: ____
Stacey R. Altman, J.D.

DEAN OF THE
GRADUATE SCHOOL: ____
Paul J. Gemperline, PhD

ACKNOWLEDGMENTS

I would like to acknowledge several people for their help with this research. First and foremost, I would like to thank my committee members, Dr. Zac Domire, and Dr. Tony Kulas, and my thesis advisor, Mr. Patrick Rider for their wisdom, tireless help, and guided freedom in the design and execution of this research. Additionally, I would like to thank Mr. Daniel Kuhman and Dr. Jamie Hibbert for their assistance and guidance during pilot testing for this research and Ms. Keleigh Britt, Mr. Aaron Abrams, and Ms. Kelsey Halstenrud for all of their assistance during data collections for this project.

Additionally, I would like to thank Dr. M. Allison Williams for first inspiring me to pursue a career in research and my family for their endless support of my education. I would like to especially thank my parents, Michael and Barbara, for making my education possible and always encouraging me to chase my dreams.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Perhaps the most serious injury for a baseball pitcher is a full tear of the ulnar collateral ligament (UCL) in their throwing arm. The prevalence of UCL reconstruction, or "Tommy John" surgery, has dramatically increased over the last 20 years and currently 25% MLB pitchers have had this procedure[13,27]. Full tears of the UCL require surgical reconstruction if the athlete hopes to return to throwing at the same level. Reports describe return-to-play rates between 65-85% and average recovery times of 10-21 months[2,8,23]. The medial elbow, including the UCL, is exposed to high valgus stresses during baseball pitching[14]. The UCL undergoes significant strain throughout the baseball pitching motion, especially in the later stages of the arm cocking phase and during the arm acceleration phase[29,31,81]. In addition to overhead throwing mechanics, elevated pitch counts and increased bullpen and game exposures are associated with increased arm, and specifically elbow, injuries at all levels of competition. There is a need for better understanding of the changes which take place in the UCL of baseball pitchers prior to injuring their throwing arm.

The UCL is the primary stabilizer of the medial elbow, and is especially critical to maintaining medial elbow integrity during baseball pitching[40]. The UCL originates on the medial epicondyle of the humerus and traverses the medial ulnohumeral joint gap to its insertion on the ulnar tubercle. Three bundles of fibers make up the UCL: the anterior bundle, the posterior bundle, and the transverse or oblique bundle[9,22,68]. The anterior bundle of the UCL has been shown to be the strongest and most important bundle of the ligament for maintaining the stability of the medial elbow[40]. As a result of its anatomic location, the anterior is the bundle most often injured and/or ruptured in baseball pitchers. In asymptomatic overhead throwing athletes, the anterior bundle of the UCL has been shown to undergo structural changes as a result of the increased valgus forces that result from the overhead throwing motion[34].

The structural properties of the medial elbow, including UCL thickness and the gap of the ulnohumeral joint, have been shown to change as a result of the stress of the baseball pitching motion. Previous studies have found the UCL space to be significantly larger between the throwing and non-throwing arms of professional pitchers, and significantly smaller although similar between arms in high school pitchers[12,52,56]. Although the literature is inconclusive, studies have shown the ulnohumeral gap to be greater in the throwing arm of baseball pitchers compared to the non-throwing arm, and have shown that this gap will significantly increase under a valgus load compared to being at rest[12,67,71]. Increases in the ulnohumeral gap with the application of valgus stress compared to the non-throwing arm have been shown to suggest significant injury to the UCL[11]. A large deficit in the literature on the UCL in pitchers is a lack of longitudinal imaging throughout a baseball season to examine how these structural properties change. Very few studies have performed pre- and post-season imaging[43], and none have performed mid-season imaging at regular intervals in order to track changes in the UCL. These studies primarily used traditional and stress radiography and sonography for the imaging of the UCL. Collecting structural property data from sonographic imaging at regular intervals throughout the season may provide insight as to when the UCL is most susceptible to significant injury. Such information would be helpful to many individuals involved with high level baseball organizations including pitching and head coaches, strength and conditioning staff, and medical personnel as they work to create training, pitching, and preventative rehabilitation programs aimed at maintaining the health of the pitchers in their organization.

The present project used ultrasound to measure changes in the structural properties of the UCL and medial elbow in NCAA Division I collegiate baseball pitchers throughout a season, and examine if any relationships exist between throwing load, upper body resistance training, and perceived elbow stiffness with changes in the properties of the UCL.

Purpose

The primary purpose of this study was to examine changes in the structural properties of the UCL and medial elbow in NCAA Division I collegiate baseball pitchers over the course of a season.

The secondary purpose of this research was to determine if relationships exist between recent throwing load, upper body resistance training, and perceived medial elbow stiffness with any observed changes in the structural properties of the UCL and medial elbow.

Significance

The present project was novel in tracking the structural properties of the UCL in baseball pitchers over the course of a collegiate baseball season. Tracking these properties will provide useful insight into both the acute and single-season chronic effects of the baseball pitching motion on pitchers' elbows. Continued study of these properties may be able to identify a change that occurs prior to a significant injury to the UCL. A discovery of such changes would be of dramatic impact with regard to preventative treatment and care of the UCL in baseball pitchers. The authors of previous research have noted the need for a reliable diagnostic test for the imaging of the UCL[77].

The present project also examined relationships between the changes observed in the structural properties and the recent throwing load, upper body resistance training, or perceived elbow stiffness for that pitcher. These relationships, in conjunction with additional research may lead to adjustments in the way in which training and throwing protocols are designed for individual pitchers, as to prevent overstressing the ligament at times when the UCL may be the most susceptible to injury.

Inclusion Criteria

1. 18 - 25 years old
2. Currently-rostered NCAA Division 1 collegiate baseball pitcher

Exclusion Criteria

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

Delimitations

1. The sample for the present project included only collegiate baseball players.
2. The sample only included baseball players who were identified on their team's roster as a pitcher.
3. Data was collected on the pitchers at regular intervals over the course of one collegiate baseball season.
4. Pre-season and post-season evaluations were conducted on both the throwing and non-throwing arm.
5. All participants in the present project underwent the same resistance training program as guided by the same strength and conditioning coach, their pitching frequency and load were

managed by the same pitching and head coaches, and their day-to-day preventative treatments were guided by the same athletic trainer with experience in professional baseball.

Limitations

1. The analysis is limited to the accuracy of the ultrasound machine and the reliability of the examiner.
2. The throwing load among the participants in this studied varied based on the role of the pitcher on the pitching staff and the amount of playing time for that individual pitcher.
3. The amount of time between a participant's most recent pitching bout and imaging sessions was not controlled.
4. The sample size used in the present project was limited in size and was collected from a single NCAA Division I collegiate baseball roster.
5. The adjustable-width arm positioning splint used in this research limited frontal plane movement to 14° at the elbow.

Operational Definitions

1. **Distraction Force -** a force applied to a body part which pulls to separate bones or joints without tearing the ligaments or skeletal musculature.
2. **Elbow Stability –** maintenance of proper alignment of the elbow joint, in this research it will specifically apply to the maintenance of proper alignment of the medial aspect of the elbow in response to an external valgus load.

3. **Medial Elbow Gapping –** Change in Ulnohumeral Gap with the addition of an external valgus load placed on the elbow
4. **UCL Length –** the length of the ligament from its origin of the ligament on the medial epicondyle of the humerus to its insertion on the ulnar tubercle
5. **UCL Thickness -** the width of only the ulnar collateral ligament, taken at 50% of the length of the ligament
6. **UCL Space –** the distance from the midpoint of the ligament to the humeral trough between the medial epicondyle and the trochlea
7. **Ulnohumeral Gap -** the distance from the most distal aspect of the trochlea of the humerus to the most proximal aspect of the head of the ulna.

REVIEW OF THE LITERATURE

Introduction

The primary purpose of this study was to examine changes in the structural properties of the ulnar collateral ligament (UCL) in collegiate baseball pitchers over the course of a season. The secondary purpose of this research was to determine if relationships exist between recent throwing load, upper body resistance training, and perceived medial elbow stiffness with the changes in the structural properties. This chapter will review the scientific literature examining: 1) the anatomy and function of the UCL, 2) the biomechanics of the baseball pitching motion, 3) changes in UCL structural properties in baseball pitchers, 4) UCL injuries and rehabilitation in baseball pitching, and 5) methods for the imaging and evaluation of the UCL.

Section 1: Anatomy and Function of the Ulnar Collateral Ligament

The ulnar collateral ligament (UCL) is located on the medial side of the elbow, crossing between the humerus and the ulna and is the primary stabilizer of the medial elbow[40]. The UCL and the radial collateral ligament are the two ligaments which act to reinforce the elbow capsule[71]. The ligament is a soft tissue complex made up of three distinct bands or bundles *(Figure 1)*: the anterior bundle, posterior bundle, and the transverse or oblique bundle[9,35,40,46,73]. The anterior bundle of the UCL originates on the

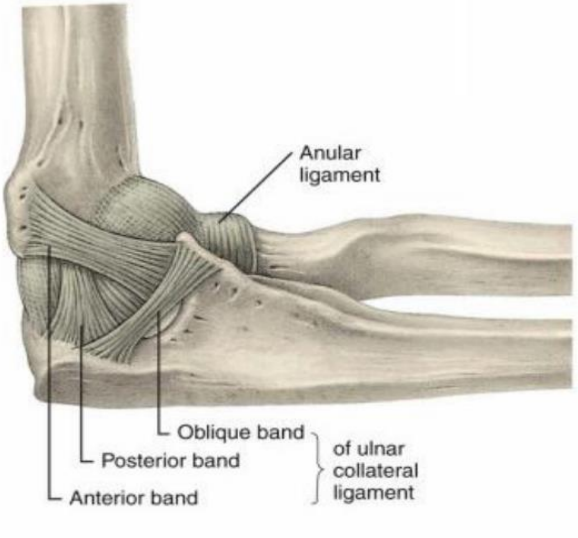


Figure 1: ***Anatomy of the Ulnar Collateral Ligament.*** Medial aspect of the elbow showing the anterior, posterior, and oblique bands of the ulnar collateral ligament[24].

medial epicondyle of the humerus and inserts on the ulnar tubercle[22,35,40,55,68]. The anterior bundle of the UCL inserts on the extreme proximal portion of the ulna. A study of 20 anatomic specimens demonstrated that the anterior bundle of the UCL inserts onto the ulna within 3.2 mm of its articular margin[7]. A second study examined the UCLs of 13 cadaveric elbows and found the edge of the ulnar insertion to be separated from the ulna articular margin by an average of 2.8mm[20]. The posterior bundle of the UCL creates the bottom of the cubital tunnel as it crosses the ulnohumeral joint with the ulnar nerve adjacent to it, while the transverse bundle travels between the insertions of the anterior and posterior bundles of the ligament[15]. The insertion of the UCL on the proximal aspect of the ulna places the ligament in a position of mechanical advantage against valgus forces[22]. The proximal attachment may appear as a uniform band of soft tissue or as it may appear to fan out and be intermingled with hyperechoic fatty tissue[40].

Previous literature has examined both the structural properties of the UCL as well as the importance of the ligament for medial elbow stability. Wavreille et al. (2008) used five cadaver specimens to measure the various lengths and limits of both the medial and lateral elbow ligaments. The study recorded ligament length and recruitment, or the length of the ligament at a specific position as a percent of the ligament’s absolute maximum length, at 0°, 30°, 60°, 90°, 120°, and 150° of flexion. The average maximum length across the positions tested for the superficial and deep limits of the anterior bundle and of the UCL were 3.94 ± 0.95 cm and 2.37 ± 0.49 cm respectively. The posterior bundle of the UCL was notably shorter than the anterior bundle with lengths of 2.2 cm ± 0.42 cm for the deep limit and 2.47 ± 0.67 cm for the inferior limit. The average length of the anterior bundle was 91.8% of the maximum length for the superficial limit and 88.6% of the maximum length for the posterior limit. The anterior limit displayed the most variation in the anterior bundle, with a minimum length of 55.9% of the maximum length[80]. The present project examined changes in the length of the anterior bundle of the UCL in pitchers at 30° of flexion over the course of a collegiate baseball season as well as differences in the length of the UCL between the pitchers' throwing and non-throwing arms.

The anterior bundle is described as the strongest and most important bundle of the UCL[14,15]. Callaway et al. (1997), found that the anterior bundle is composed of two distinct bands of fibers which tighten reciprocally as the elbow goes through flexion and extension[9]. Munshi et al. (2004) dispute these findings, claiming that although a pseudolaminar appearance could be seen microscopically, there were no distinct findings to account for the presence of more than one layer of the anterior bundle[55].

The anterior bundle is considered to be the primary stabilizer of the medial elbow against valgus forces[12,35,53,68]. The UCL is able to maintain elbow stability even in the event of a fractured and separated olecranon process of the ulna, as long as the ligament remains intact[68]. The extent to which the UCL contributes to medial elbow stability does appear to be dependent on the angle of the elbow joint. Morrey and An (1983) found that the anterior bundle of the UCL contributes up to 31% of the resistance to applied valgus forces when the elbow is in full extension and as much as 54% when the elbow is flexed 90°. Similarly, the anterior bundle of the UCL has been shown to provide up to 78% of resistance to joint distraction forces when the elbow is flexed 90° [54]. A distraction force pulls to separate the elbow joint and can be identified when the component of the resultant force acs along the long axis of the upper arm[81]. Large valgus forces and distraction forces are seen in the medial elbow and specifically on the UCL during the pitching motion. The importance of the UCL in maintaining the structural integrity of the medial elbow makes it essential for proper arm function during dynamic upper body movements such as the baseball pitching motion.

Section 2: Biomechanics of the Baseball Pitching Motion

The overhead throwing motion used by pitchers in baseball as well as by throwers in other activities including football and javelin is a complex motion which generates large amounts of stress throughout the throwing arm[48]. In order to fully understand the role of the elbow in the pitching motion, we must first have an understanding of the entire pitching motion itself. Initially, the pitching motion was separated into the cocking, acceleration, and follow-through phases[60,79]. However more recent research describes the pitching motion in six phases in order to simplify the examination and interpretation of the biomechanics throughout the pitching motion. The six phases of the pitching motion are, in order: wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow-through[17,29,31,48,81] *(Figure 2).*

Section 3a: Wind-Up Phase

The pitching motion begins with the wind-up phase as the pitcher makes their initial movement to begin the motion. This phase includes the lifting of the front leg, and ends when the front leg has reached its peak height before accelerating towards home plate and as the throwing hand separates from the glove hand[29,81]. During the wind-up phase, the pitcher is moving the body to a

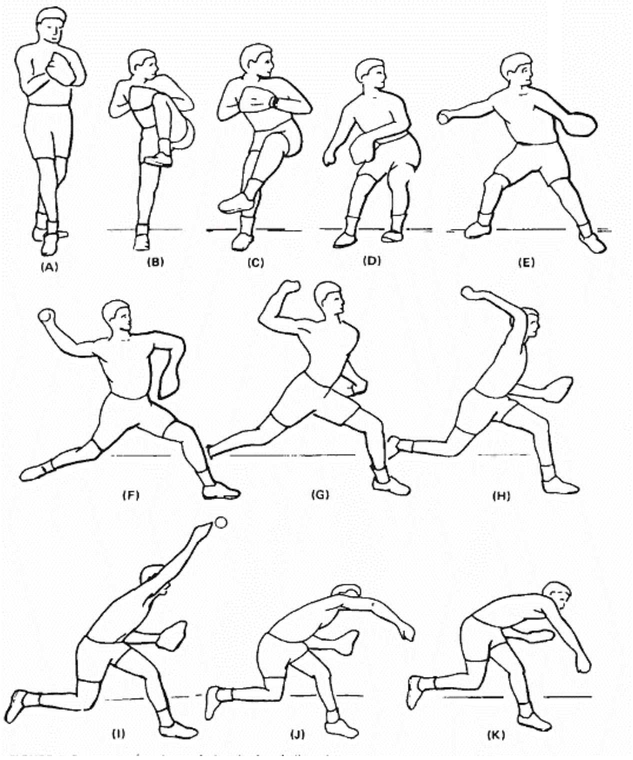


Figure 2. ***Phases of the Baseball Pitching Motion.*** The six phases of the pitching motion are the wind-up (A-B), stride(C-E), arm cocking (F-G), arm acceleration (H-I), arm deceleration (J), and the follow-through (K)[9].

more powerful position, balancing over his rear leg with his throwing elbow in a flexed position, and there is very little movement at the elbow[48]. The UCL is relatively stable and stationary throughout the wind-up phase of the baseball pitching motion.

Section 3b: Stride Phase

The pitching motion continues with the stride phase, beginning as the lead leg starts moving towards home plate and the arms continue to separate, and concluding when the lead foot makes contact with the mound[29,48,81]. The elbow is extended through the beginning and middle of the stride phase, and begins to move into flexion until it ultimately reaches a positon between 80-100° of flexion at the time the lead foot makes contact with the mound[48,81]. The positioning of the lead foot at the end of the stride phase can have significant impact on the biomechanics of the elbow through the rest of the pitching motion. One potential concern during this phase is the lead foot landing in an excessively toe-out positon as a result of external rotation at the hip greater than 90°. A second potential concern during the stride phase is the lead foot landing while the hip of the lead leg is hyperextended. In either of these scenarios, there is the possibility that the pelvis will rotate too early in the pitching motion, causing the torso and shoulder girdle to begin their forward rotation while the throwing arm is still is still moving slightly backwards and preparing to begin its forward motion. This opposition of rotation caused by a deviation from proper foot and pelvis mechanics during the stride phase will produce increased forces in the anterior shoulder and medial elbow. Additionally, if there is insufficient or excessive external rotation of the shoulder at the end of the stride phase, the throwing arm may lag behind the rest of the body and the shoulder girdle. Increased valgus forces at the elbow resulting from either improper positioning of the stride foot or from a deviation from proper external rotation of the shoulder will place additional stress on the UCL in the subsequent phases of the pitching motion[31].

Section 3c: Arm Cocking Phase

The arm cocking phase follows, ending when the throwing arm has reached a position of maximal external rotation[29,48,81]. Large forces and torques are seen in both the shoulder and elbow as the arm cocking phase progresses. During this phase of the pitching motion, an internal rotation torque of 67 ± 11 Nm, a horizontal adduction torque of 87 ± 23 Nm and an abduction torque of 44 ± 17 Nm are generated at the shoulder. Likewise, 310 ± 100 N of anterior force, 250 ± 80 N of superior shear force, and 480 ± 130 N of compressive force were produced in the shoulder[29]. After the lead foot makes contact with the mound, the trunk and pelvis begin rotating towards home plate creating a minor flexion torque at the elbow of 0-32 Nm[29,48]. The late cocking phase is often considered the period of the pitching motion in which the greatest stress is placed on the UCL as it goes through an abrupt, tremendous increase in valgus stress[12,56,67,71]. In the latter part of the arm cocking phase, the elbow is flexed 95° ± 10° and the glenohumeral joint is externally rotated 165° ± 11°, abducted 94° ± 21°, and horizontally adducted 11° ± 11°, which results in the generation of a large valgus torque onto the upper arm at the elbow[29,48]. This valgus torque is resisted through the generation of a varus torque of 64 ± 12 Nm on the forearm just prior to the maximum external rotation of the shoulder[48,81]. Additionally, 300 ± 60 N of medial force, 160 ± 80 N of anterior force, and 270 ± 120 N of compressive force was produced on the elbow towards the end of the arm cocking phase[29]. The generation of the large valgus forces and accompanying varus torques in the elbow during the late stages of the cocking phase perhaps makes the UCL most susceptible to injury during this portion of the pitching motion.

Loftice et al. (2004) identify one potential limitation in the study by Morrey and An (1983), described previously in this review, in that their study was performed on cadavers. This means that the resistance to stress on the elbow could not have had any contributions from muscular contraction. In vivo, contraction of the wrist flexor pronator group, in addition to the anconeus and triceps brachii appear to also provide varus torque, perhaps reducing the stress seen on the UCL[81]. Additionally, if the UCL were responsible for 54% of the 64 Nm varus torque during the arm cocking phase, it would be nearing or even exceeding the maximum capacity of the ligament, which has been shown to be approximately 32.1 ± 9.6 Nm[18,29].

Shortly before maximal external rotation, the biceps brachii show a marked decrease in muscle activity, allowing the centrifugal force from the transverse rotation of the shoulders towards home plate to lead to a rapid extension of the elbow[81]. At the same time as the large decrease in biceps activity, there is also an increase in muscle activity in the triceps brachii, although it appears that the decrease in biceps activity is more responsible for the rapid elbow extension rather than the increase in triceps activity. Roberts reported that a pitcher whose triceps had been inactivated using a peripheral nerve block was still able to throw at more than 81% of the velocity produced prior to receiving the nerve block[63]. Her findings demonstrate the potentially minor role of the triceps during the rapid extension of the elbow in this phase. One potential risk factor for pitching injuries during the arm cocking phase is increased horizontal adduction of the shoulder. Anterior shoulder force, medial elbow force, and horizontal adduction shoulder torque all increase in pitchers who excessively adduct the shoulder horizontally during the arm cocking phase[31]. This is often described in lay terms as a pitcher "leading with the elbow." Such a pattern is often seen in pitchers with a compromised UCL as it lowers the varus torque produced in the elbow, and subsequently lowers the strain on the UCL. However, this alteration of pitching mechanics places additional stress on the shoulder joint and may be one explanation of shoulder injuries in pitchers with previous elbow injuries[31].

Section 3d: Arm Acceleration Phase

Next is the arm acceleration phase, which continues the pitching motion until the ball is released from the throwing hand[29,48,81] The arm acceleration phase is the shortest, most dynamic, and most intense phase for the throwing arm. Throughout the arm acceleration phase, the elbow goes through extension as the forearm swings out to the side of the pitcher and the trunk continues to rotate forward[48,81]. The elbow reaches a maximum extension velocity between 2100°/s and 2700°/s, which is most likely due to the rotary actions of several body segments and not solely because of the elbow extensors[48] Throughout this rapid extension at the elbow, centrifugal force applies a large distraction force on the elbow joint which is countered by a compressive force of 800-1000N applied by the triceps, wrist flexors, and anconeus in order to maintain elbow integrity[48,81]. A substantial varus torque is also generated during the arm acceleration phase in order to resist valgus elbow torque and accelerate the forearm forward into the ball release[48]. As Morrey and An (1983) explain, the UCL aids in the dissipation of these large displacement forces and valgus torques on the medial elbow[54].

Section 3e: Arm Deceleration Phase

After ball release, the baseball pitching motion continues with the arm deceleration phase until the arm reaches maximum internal rotation[29,48,81]. In this phase, it is necessary for the arm to be decelerated from its rapid forward motion and its energy dissipated through the shoulder and elbow. Regarding stress at the shoulder joint, the arm deceleration phase is described as the second critical instance in the pitching motion, after the late cocking phase[29]. At this point, a peak compressive force of 1090 ± 110 N, or close to 90% of the pitcher's body weight, is seen at the shoulder in order to prevent excessive arm distraction[29,81] Deceleration at the elbow occurs as a result of a flexor torque prior to full extension created by an eccentric contraction of the biceps brachii[81]. The elbow is flexed only 25° ± 10° while the arm is externally rotated 64° ± 35°, abducted 93° ± 10°, and horizontally adducted 6° ± 8° at the shoulder during this phase of the pitching motion. The wrist extensor muscles also play a large role in the arm deceleration phase by eccentrically decelerating the wrist flexion that occurs after ball release[81]. Overall, the pitcher's throwing shoulder is under much greater stress during the arm deceleration phase in comparison to the medial elbow and the UCL.

Section 3f: Follow-Through Phase

The final phase of the pitching motion is the follow-through. The follow-through begins with the arm in maximum internal rotation and finishes when the pitcher reaches a balanced fielding position[29,48,81]. The motion of the larger body parts including the trunk and legs continues to dissipate the energy from the throwing arm while the elbow returns to a more comfortable, flexed position in front of the body[29,48,81]. The UCL returns to a less stressed and more stable position as the throwing arm becomes stationary again at the end of the throwing motion.

Throughout the overhead baseball pitching motion the medial elbow undergoes several periods of heavy stress in which the UCL must counter as the primary stabilizer of the medial elbow. Specifically, the late stages of the arm cocking phase and the arm acceleration phase are the most strenuous for the UCL in particular, and the pitcher's throwing arm as a whole.

Section 3: Changes in UCL Structural Properties in Baseball Pitchers

The thickness of the UCL is one of the structural properties of the ligament which has repeatedly been shown to change in the throwing arm and to differ from the non-throwing arm as a result of baseball pitching. In previous research, there are two conflicting definitions of "UCL thickness." For the purpose of this review, we defined the width of only the ligament as "UCL thickness," and measurements from the midpoint of the ligament to the humeral trough between the medial epicondyle and the trochlea was referred to as "UCL space" (*Figure 3).* One study using MRI to examine the properties of the UCL in both arms of 23 high school baseball pitchers found asymmetric thickening of the anterior band of the UCL in the throwing arms of 65% of the pitchers included in the study[38]. Marshall et al. compared the throwing and non-throwing elbows of high school pitchers and reported non-significant differences of 6.54 mm in throwing arm compared to 6.71 mm in the non-throwing arm with regards to the UCL space. The study also reported non-significant differences for UCL thickness of 1.85 mm in the throwing arm compared to 1.89 mm in the non-throwing arm[52]. Another study described significant differences in the UCL space of the pitching arm (6.3 ± 1.1 mm) compared to the non-throwing arm (5.3 ± 1.0 mm) at rest, and with application of a valgus force (6.3 ± 1.4mm compared to 4.8 ± 0.9mm)[56]. The dominant elbows from a sample of

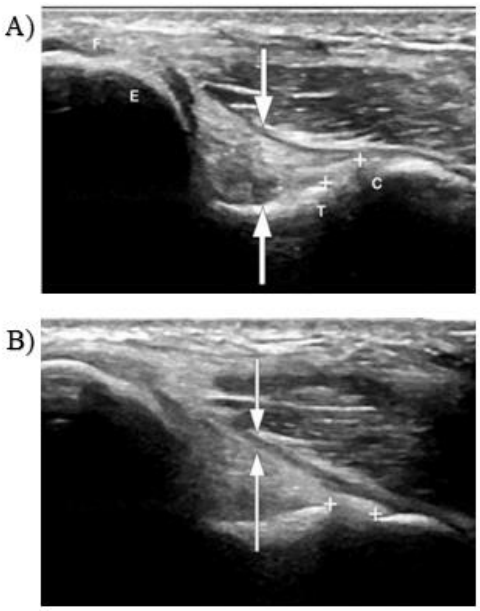


Figure 3. ***UCL Thickness compared to UCL Space.***

A) UCL Space, shown as the distance between the midpoint of the UCL and the humeral trough between the medial epicondyle and the trochlea.

B) UCL Thickness, shown as the thickness of the UCL itself.

Marshall et al. 2015[16]

368 professional baseball pitchers had a mean UCL space of 6.15 ± 1.57 mm, which was significantly greater than the mean UCL space of 4.82 ± 1.32 mm in the non-throwing arms[12]. A sample of 22 high school varsity pitchers experienced significant UCL thickness increases from 1.85 ± 0.51 mm in their preseason evaluation, to 2.20 ± 0.71 mm in their postseason evaluation[43]. The findings by Keller et al. (2015) show that changes in the thickness of the UCL can take place in as little as one season, which the current project examined using pre-season and post-season imaging, as well during the course of a collegiate baseball season. The increases in UCL thickness was significantly correlated ($r = 0.60$, $P = 0.01$) with increased number of bullpen sessions thrown per week[43], which lends itself towards the belief that chronic UCL adaptations can be early signs of overuse injuries in overhead throwing athletes. The present project also used questionnaires to track the number of bullpen sessions and in-game/scrimmage innings thrown over the course of the season.

Another characteristic of the throwing arm elbow which baseball pitching has been shown to have an effect on is the ulnohumeral joint gap spacing of the medial elbow. Sasaki et al. reported significant differences between a mean ulnohumeral joint space of 2.7 mm in the throwing arm and 1.6 mm in the non-throwing arm of 30 collegiate baseball players. These differences ranged from -.05 to 5.2 mm in the baseball players compared to -0.4 to 0.4 mm in a healthy control (non-baseball players) group. There was also a significant difference in the medial elbow gapping in players who had reported medial elbow pain while throwing compared to players who had never experienced medial elbow pain[67]. A study of 26 major league professional baseball pitchers did not find a significant difference in ulnohumeral joint gapping between the pitching and non-throwing arms at rest, however, when valgus stress was applied, the joint space of the pitching arm (4.2 ± 1.5 mm) was significantly greater than that of the non-throwing arm (3.0 ± 1.0 mm)[56].

Ciccotti et al. also found the ulnohumeral joint space in dominant arms to be significantly greater at 4.56 mm compared to 3.72 mm in the non-throwing arm when placed under valgus stress. These values resulted in increases of 1.24 mm in the dominant arm and 0.78 mm in the non-throwing arm compared to the joint gapping measurements at rest[12]. In contrast, Singh et al. concluded that there was not a significant difference between overhead throwing athletes and non-overhead sports with regard to joint gap spacing in the medial elbow[71]. As mentioned previously, Rijke et al. (1994) used stress radiography to evaluate the medial elbows of 46 individuals (42 symptomatic) and concluded that a difference in increase in the medial joint line opening between an individual's elbows was greater than 0.5 mm, then the symptomatic elbow had a tear of the UCL[62]. The use of 0.5 mm of increased laxity compared to the contralateral elbow was supported by research conducted by Ellenbecker et al. (1998), in which the uninjured elbows consistently demonstrated smaller differences in medial elbow laxity with the application of stress compared to the injured elbows. However, in a study by Singh et al. (2001) 25% of the athletes evaluated had valgus laxity increases greater than 0.5 mm, yet were asymptomatic. When using MRI or stress radiography to image the UCL, widening of the ulnohumeral joint greater than 2 mm compared to the contralateral side suggests either a full thickness tear of the UCL or significant valgus instability of the elbow[77]. The numerous studies which report increases in the ulnohumeral joint gapping space in the throwing arm of baseball pitchers aid in the understanding of the large stresses placed on the UCL as it attempts to stabilize the medial elbow throughout the throwing motion. However, there is still a need for additional research in this area to provide more conclusive information on structural changes in the UCL that may either place a pitcher at an elevated risk of injury, or be indicative of the presence of injury. This need is demonstrated by the wide range of conclusive statements from previous research, such as the difference between 0.5 mm[62] compared to 2.0 mm[77] being indicative of a torn UCL. Authors of previous research on UCL injuries in baseball have noted the need for a reliable diagnostic test for the imaging and evaluation of the UCL[77].

Section 4: Ulnar Collateral Ligament Injuries in Baseball Pitching

The UCL is the most commonly injured soft tissue structure in the elbow of overhead-throwing baseball pitchers and has received a lot of attention in the scientific literature[41,48]. The majority of elbow injuries in pitchers occur on the medial side, where the UCL is located and is the main stabilizer. In fact, 68-90% of reported elbow pain in pitchers is due to symptoms originating from the medial aspect of the elbow[10,50]. In a study of more than 350 professional baseball pitchers, 3.3% of them experienced partial or complete damage of the anterior band of the UCL during the length of the study, although it should be acknowledged that the study length was less than 2 years for more than 240 of the pitchers in the study[12]. Lyman et al., found that almost 50% of 476 youth pitchers reported elbow or shoulder pain at least once during a season[49]. In a separate study, Lyman et al. also reported 47% of pitchers between the ages of 9 and 12 years old reported elbow or shoulder pain throughout the course of the study[50]. Additional research has also reported that the approximate 50% injury rate reported by Lyman et al. and appears to be consistent among professional baseball pitchers as well[49,79]. A one-season study of 22 high school level pitchers also found that 41% of those pitchers complained of arm pain while throwing at least once during the season[43]. In high school athletes, most UCL injuries manifest themselves during a single pitch, in which a pop can be heard or a tearing sensation becomes present in addition to medial elbow pain[61]. The frequency at which baseball pitchers experience medial elbow pain is significant as injuries to the anterior bundle of the UCL most commonly manifest as pain in the medial elbow of overhead throwers[14].

There are several risk factors associated with increased elbow pain in pitchers. Analyzing 298 youth pitchers, increasing age, weight, and lower height were found to be significant independent risk factors for the incidence of elbow pain[50]. One notion behind this occurrence is the late development of the secondary ossification centers of the elbow, which do not completely ossify and fuse to the long bones until as late as age 17[59]. These secondary ossification centers are the most vulnerable areas of the elbow in youth pitchers and can become inflamed and irritated during throwing[50]. The prospect of elbow injuries in pitchers appears to be related to the number of pitches thrown in an individual game, the total number of pitches thrown in a season, and the pitch types used by the pitcher. In youth pitchers, the likelihood of elbow pain increases 6% with every 10 in-game pitches thrown, and increases over 50% with any pitch count above 75 pitches. Pitchers who played and/or pitched in games and scrimmages outside of their league-sanctioned contests were at a significantly greater risk of experiencing elbow pain. Pitchers who threw pitches such as a forkball, splitter, or sinker which use a split finger grip were at an increased risk of elbow pain. Perhaps the most useful metric associated with elbow pain in pitchers is self-reported arm fatigue. Both arm fatigue and elbow stiffness in the previous game were strongly associated with an increase in elbow pain[50].

The current project used a questionnaire to allow for the self-reporting of elbow stiffness and pain by the pitchers at each evaluation throughout the study period. Petty and his colleagues at the American Sports Medicine Institute have seen a dramatic increase in baseball players requiring UCL surgery as well as in the proportion of those athletes who are in high school. They hypothesize that an excessive amount of competitive throwing, throwing breaking pitches, high fastball velocity, or inadequate warm-ups may be some of the causes of the increase in high school pitching injuries[61].

Injuries to the UCL in baseball pitchers were made famous by Tommy John, a left-handed pitcher for the Los Angeles Dodgers, who was the first person to undergo a complete reconstruction of the UCL in 1974[35]. As such, a tear of the UCL is commonly referred to as the "Tommy John Injury," and the subsequent surgical repair is known as having "Tommy John Surgery." The majority of symptomatic UCL tears in baseball pitchers are the result of the chronic, repetitive elbow trauma seen as a product of pitching[6,12,53]. Fortenbaugh (2009) explains that injuries are most likely when the pitcher transitions through vulnerable positions while repeatedly applying high forces and/or torques to susceptible tissue, such as the UCL. Greater stress on the UCL can be a result of protection of the medial elbow during pitching due to poor mechanics, lack of flexibility and conditioning, and/or muscular fatigue[22].

Conservative treatment of UCL injuries is a combination of a rest period, stretching and strength rehabilitation programs, and then finally a graduated and monitored return to throwing program. Two primary goals of this style of conservative treatment are to relieve any pain and inflammation in the symptomatic elbow, and to increase the functional strength of the elbow and forearm[53]. Conservative treatment strategies are more likely to be seen with pitchers suffering from only a partially-torn UCL.

Complete tears of the ulnar collateral ligament will require surgical reconstruction if the athlete hopes to return to pitching at the same level which they were able to prior to the injury. Complete UCL reconstructions are strenuous on the elbow, and it is not a guarantee that the athlete will ever return to their prior level of competition after the lengthy rehabilitation period. In follow up studies on Major League pitchers who underwent UCL reconstruction, approximately 80% of the pitchers successfully returned to pitch in at least one Major League game[23,51]. However, it must also be recognized that the percentage drops to 67% if only those pitchers that are able to pitch in at least 10 games in one season are considered "successful,"[51].

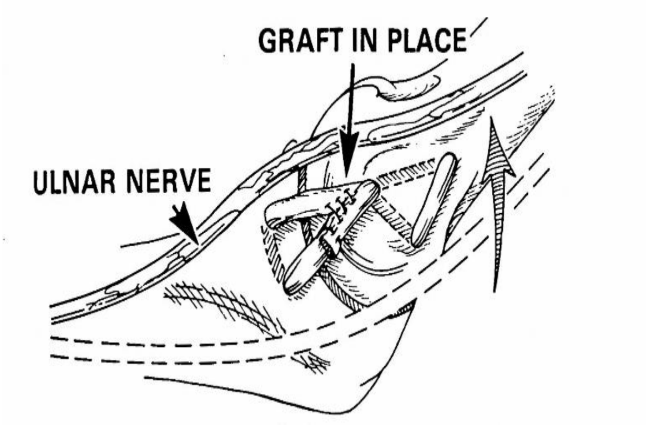


Figure 4. *Docking Method for Ulnar Collateral Ligament Reconstruction.* The docking method used in a complete reconstruction of the ulnar collateral ligament, in which a tendon graft is woven in a figure-eight pattern through tunnels which have been drilled into the ulna and the humerus[41].

One of the studies examining Major League pitchers reported an average recovery time of 20.5 months[5]. In the most comprehensive follow-up study in the literature, 743 athletes who had undergone UCL reconstruction at least 2 years prior were completed the follow up questionnaire. 83% of these athletes were able to return to their previous level of competition, and the average time to full recovery was 11.6 months. The report did acknowledge that complications occurred in 20% of patients, with 4% being considered major complications. The most common complication was minor postoperative ulnar nerve neurapraxia, which occurred in 18% of the pitchers involved in this study[8]. When focusing on high school athletes, Petty et al. report a 74% successful return-to-play rate out of 27 high school UCL reconstruction surgeries. Tears of the UCL are likely to be accompanied by a noticeable reduction in pitching velocity and control during throwing[6]. This becomes problematic given that baseball coaches most often claim that control and velocity are what makes a pitcher effective (Fortenbaugh et al., 2009). One of the methods of surgically reconstructing a UCL tear is the "docking method." This method involves using a graft from the palmaris longus or gracilis and inserting that graph through bone tunnels drilled in the ulna and humerus[5] (*Figure 4).* Dr. Frank Jobe, who performed the first UCL reconstruction, performed a total of 16 complete reconstructions of the ligament from 1974 to 1982. Of those 16 athletes, 10 of them were able to return to their prior level of competition, and one returned to competition at a lower level, and five retired from professional athletics, although not due to the procedure. Seven of the eleven athletes were able to return to full activity within one year of the surgery and the remaining four had returned with one and a half years[41]. Jobe et al. (1986) also describes the process by which the graft was reconstituted into the ligament. After the reconstruction surgery, there is a slow revascularization by way of the sheath of granulation tissue which will grow from the tissue adjacent to the implantation of the graft. The new tissue will encircle the graft and supply it with new vessels, completing the healing process[41]. Understanding the complication rate and percent of players that do not return to their prior competition level, monitoring changes in the UCL throughout the course of a season is additionally relevant in an effort to learn more about predicting and preventing these injuries.

Section 5: Methods for the Imaging and Evaluation of the UCL

There have been several different methods used in previous literature to examine the integrity and properties of the UCL. These methods include surgical observation, traditional and stress radiography, magnetic resonance imaging, computed tomographic arthrography, and traditional and stress sonography[32,82]. Each one of these methods has its own unique balance of benefits and disadvantages as a modality for the imaging and evaluation of the UCL.

Section 1a: Surgical Observation

Surgical observation is useful in the diagnosis of partial thickness tears in patients who may be symptomatic of a UCL tear, yet in which the ligament appears intact during non-invasive imaging tests. It is not uncommon in partial thickness tears for the most superficial portion of the ligament to be intact, leading to false negative readings on MRI, CT arthrography, and even stress sonography readings[77].

Section 1b: Traditional and Stress Radiography

Traditional and stress radiography has long been used to image and investigate the integrity and condition of various soft-tissue elements of the body. In previous literature, stress radiography has been most commonly used as a method of examining the medial elbow and the ulnar collateral ligament[14,46,71]. Conway et al. (1992) reported on 68 patients with valgus instability of the elbow from 1974-1987. Almost 70% of those patients received traditional and stress radiographs as a component of their pre-operation evaluations. Lee et al. (1998) used stress radiography to evaluate medial elbow gapping, or the increase in U-H gap with the application of a valgus load, in 40 healthy individuals and found significant increases in the U-H gap space with the introduction of either gravity stress or a 5 lb. valgus stress compared to an unstressed condition. These findings show the importance, and usefulness, of using an imaging modality such as radiography to compare a symptomatic elbow to the contralateral elbow in order to decrease the incidence of false-positive diagnoses based solely on medial elbow laxity. Stress radiography for the UCL is performed using stress applied either manually or mechanically to the lateral side of the elbow in order to create a valgus force across the joint[14]. The mechanical tool most commonly used to create such a force is the Telos GA-IIE device, which is able to provide a consistent force application while also keeping the elbow flexed at a constant angle. Previous studies using the Telos device have shown an intraclass correlation coefficient of 0.95[12,14,22].

Some of the downfalls of using radiology to image and measure the UCL include the costs associated with x-ray imaging as well as the fact that these machines are not always easily accessible in a wide range of settings[6]. Perhaps the greatest drawback from using traditional or stress radiography to image the UCL in baseball pitchers is that each imaging session exposes the athlete to ionizing radiation[6]. This particular concern becomes elevated with the consideration of regularly scheduled imaging sessions over the course of a baseball season in order to track changes in the ligament, such as in the current project. The accuracy of radiographic images for accurate diagnosis of UCL injury has been inconsistent in previous literature. Rijke et al. (1994) used stress radiography to evaluate the medial elbows of 46 individuals (42 symptomatic) and concluded that a difference in increase in the medial joint line opening between an individual's elbows was greater than 0.5 mm, then the symptomatic elbow had a tear of the UCL. The use of 0.5 mm of increased laxity compared to the contralateral elbow was supported by research in which the uninjured elbows consistently demonstrated smaller differences in medial elbow laxity with the application of stress compared to the injured elbows[22]. Conversely, 25% of the athletes evaluated in a study by Singh et al. (2001) were asymptomatic, yet had valgus laxity increases of greater than 0.5 mm.

Section 1c: Magnetic Resonance Imaging

The use of magnetic resonance imaging (MRI) has been considered by many to be the gold standard for the evaluation and diagnosing of medial elbow soft tissue injuries. MRI is reported to be able to determine the presence of both partial and full-thickness tears of the UCL[55,67,77]. MRI can play a vital role in diagnosing injuries to the UCL, since the humerulnar joint and the integrity of the UCL can be difficult to evaluate at during a clinical exam[55]. In 14 patients with UCL tears, MRI readings correctly diagnosed all seven who had full-thickness tears of the ligament, however only one out of the seven subjects (14%) with partial tears of the UCL were correctly diagnosed. Thus, the use of MRI for the diagnosis of full-thickness tears of the UCL has been shown to have a specificity of 100%[77].

Arthrography, in which contrast is injected into the joint capsule to highlight abnormalities in the image, is commonly used when performing MRI on an injured pitcher. MR arthrography is considerably expensive and time-intensive, and elite level baseball pitchers tend to be particularly protective of their pitching arms and are hesitant about having needles inserted into their throwing elbows[56]. Additionally, MRI is a static imaging technique, which is not able to image and demonstrate medial elbow instability, which is critical in the pathophysiology of injuries to the UCL[56]. The use of MRI to diagnose partial tears of the UCL in baseball pitchers has not been excellent in previous research as accuracies as low as 57% (8 out of 14) have been reported for the correct identification significant structural UCL injuries[77].

Section 1d: Computed Tomographic Arthrography

Computed tomographic (CT) arthrography is another tool used for the evaluation of the medial elbow which is also able to detect partial tears as well as full-thickness tears of the UCL. CT arthrography correctly identified 86% of UCL abnormalities in individuals with partial or full-thickness tears, and showed abnormalities in just one of nine individuals with intact UCLs. When comparing the ability of CT arthrography and MRI to diagnosing full-thickness tears of the UCL, CT arthrography demonstrated a sensitivity of 100%[77]. The primary drawbacks with CT arthrography include its high cost for evaluation and the same hesitation by pitchers when having needles inserted into their throwing elbows[56].

Section 1e: Traditional and Stress Sonography

Many studies on the integrity of the structural properties of the UCL have used traditional and/or stress sonography to evaluate the ulnar collateral ligament[6,12,15,43,52,56,82] Benefits of the use of stress sonography to reliably and precisely examine ligaments in the body include the ability to image ligaments through a non-invasive, non-radioactive method compared to radiological imaging methods. Ultrasonic imaging has a higher resolution than MRI, allowing it to display better depiction of fine nerves as well as the subtle fibrillary details of tendons and ligaments[15]. As such, stress sonography has been shown to have the ability to detect acute and chronic changes in the UCL including degeneration of the ligament, calcification and ossification within the ligament and partial and full-thickness tearing of the UCL[16,56,82]. One case has even reported two cases in which sonography was used to evaluate the integrity of the UCL and extent of UCL injury after MRI was not sufficient[16]. Additionally, ultrasound machines allow for much quicker imaging and has much greater portability compared with radiography, CT arthrography, and MRI[32,52,56,82]. The use of ultrasound to evaluate the UCL also allows the examiner to apply external forces during the live dynamic imaging of the ligament[82].

With regard to reliability, Bica et al. (2015) showed stress sonography to have intraclass correlation coefficients of 0.75-0.94 with standard errors of measurements between 0.3-0.4mm for ulnohumeral joint gapping in the medial elbow. The study also reported intraclass correlation coefficients from 0.72 to 0.91 with standard errors of measurement between 0.6-0.9mm for measuring the length of the UCL. These values display that stress sonography has moderate to excellent reliability and excellent precision for measuring joint gapping and the length of the UCL. A study of 22 high school varsity pitchers was conducted using stress sonography to measure UCL consistency and thickness as well as the width of the ulnohumeral joint space. This study reported an intraclass correlation coefficient of 0.67, suggesting good agreement between the two different evaluators used in the study[52]. The reliability, non-invasive nature, portability, and ability to perform dynamic imaging make ultrasonic imaging an excellence modality for imaging the UCL in baseball pitchers.

In addition to measuring the structural properties of the ligament using B-mode ultrasound, ultrasound elastography can be used to measure the material stiffness of a soft-tissue structure. Ultrasound elastography was first described as a new method for strain and elastic modulus imaging in order to determine the stiffness of soft tissue in the early 1990s by Ophir and his colleagues[47,58]. Elastography is able to be performed in conjunction with MR and ultrasonic imaging[47,58]. At the time, the potential medical applications of ultrasound elastography were mainly directed towards the detection and evaluation of tumors, such as in breast and prostate cancer, liver disease and muscle disease[47,58]. The stiffness of a material is described using a quantitative measure referred to as Young's elastic modulus. In the scientific community, interest in ultrasound elastography has continued to grow since its introduction by Ophir et al. in 1991 due to increasing availability of imaging technology and a further understanding of its potential applications[19].

The stiffness of any body of soft tissue cannot be measured directly in vivo because stiffness is a function of the elastic modulus of the tissue and its geometry. As such, an external mechanical stimulus must be applied to the tissue which can precisely track fine motion and propagation within the tissue, such as ultrasound, magnetic resonance imaging, or a different diagnostic imaging method[57]. For the purposes of this project, this review will focus on the use of ultrasound as the mechanical stimulus. There are four main types of ultrasound elastography in use today: strain elastography, acoustic radiation force impulse elastography, transient elastography, and shear wave elastography[19].

The most common form of ultrasound elastography in use today is referred to as strain elastography or compression elastography, in which a compressive force is applied to the soft tissue causing axial strain. The strain is then calculated by comparing the echo sets from the ultrasound machine before and after the compressive force is applied[47,58]. In strain elastography, the stress applied to the tissue is assumed to be uniform, and every place along the tissue will experience some amount of strain, with stiffer elements of the tissue experiencing less strain than less-stiff elements[57]. The elastic modulus is inversely proportional to the strain measured in the tissue. Attempting to maintain a consistent manual compressive force is the largest disadvantage when using strain elastography. Strain ultrasound elastography is used mainly in oncological settings to detect tumors in several different types of cancer and is also widely used in musculoskeletal applications[19]. However, there is one previous study which used strain elastography to measure the stiffness of the coracoacromial ligament. A negative correlation ($r = -0.825$, $P<0.01$) was found between a participant's age and the stiffness of their coracoacromial ligament[44].

A second type of ultrasound elastography in use in clinical practice is acoustic radiation force impulse (ARFI) elastography. The main difference between strain elastography and ARFI is that the tissue is excited internally during ARFI by the pulse emitted from the ultrasound probe, instead of externally through compression. The excitation creates shear waves propagating away from the region of excitation. Stiffer portions of soft tissue will experience less displacement and greater shear wave velocities than softer tissues as the pulse travels through the tissue[19,70]. ARFI is able to measure deeper tissues in the body which are not able to be stressed through external compression, and is mainly used for the imaging of the liver, thyroid, and breast[19]. ARFI has been used to study stiffness in a variety of tissues, most notably liver fibrosis[19,70]. One of the disadvantages of AFRI elastography is that research has shown the velocity of the resulting shear waves to be dependent on the amount of compressive force applied by the examiner[70,74,78].

One of the downfalls of traditional strain elastography is that there is a bias created with regard to reflecting waves that are created at tissue boundaries[47]. Transient elastography uses a short-tone burst of vibration as an external stimulus to excite shear waves within the tissue. The short-tone burst allows for the separation of forward propagating waves from reflecting waves using a pulse-echo system[47,66]. This method also uses estimates of the shear wave velocity through the tissue of interest in order to calculate Young’s modulus. The short bursts of waves allow for the distinction between the forward waves initiated by the ultrasound probe from those which are reflecting from the stimulated tissue[47,66]. In previous literature, transient elastography has most commonly been used for the evaluation of liver stiffness for aid in diagnosing various liver pathologies[12,26,33,76]. However, transient elastography has also been used in musculoskeletal research to quantitatively measure the elastic properties of the calcaneal tendon and the gastrocnemius muscle, often with regard to the effect of stretch on the elastic nature of the muscle-tendon unit[1,75].

Shear wave elastography is another type of ultrasound elastography currently in widespread use and emerging as a promising diagnostic tool for evaluating the mechanical properties of skeletal muscle[19,21]. The ultrasound probe produces pulsed ultrasound waves to create an internal stimulus within the soft tissue being imaged. When the ultrasound waves produced by the transducer interact with soft tissue, shear waves are created and propagate perpendicular to the axial strain in the tissue. Shear wave elastography is based on measuring the velocity of the shear waves produced within the soft tissue and calculating Young's modulus from that velocity[4]. Shear wave ultrasound elastography produces a color-coded elastogram as both a qualitative depiction of tissue stiffness as well as quantitative maps of either tissue elasticity in kPa or of the velocity of the shear waves in cm/s. Shear wave elastography produces the traditional gray-scale B-mode image normally shown with traditional ultrasound in addition to the color-coded elastogram. This method of elastography is reported to be more objective than strain elastography because there is no compression of the tissue required and the resulting measurements provided are a direct quantitative evaluation of the elasticity of the tissue[19].

As with the other types of ultrasound elastography, perhaps the most common clinical use of shear wave elastography is for detection of abnormalities in lymph, liver and breast soft-tissues[3,24,25]. There are several musculoskeletal soft-body structures in which literature has demonstrated the use of shear wave elastography to measure the stiffness in, include the Achilles tendon, supraspinatus, transversus abdominis, and the hamstrings muscles[36,37,39,45,64,72]. However, there seems to be a scarcity of literature describing the use of shear wave elastography for the evaluation of ligament stiffness in vivo. A recent study which used shear wave elastography when measuring coracohumeral ligament stiffness in individuals with adhesive capsulitis of the shoulder found increased stiffness in the shoulder which was symptomatic of adhesive capsulitis compared to coracohumeral ligament of the asymptomatic contralateral shoulder[83].

In comparison to other methods discussed in this review, shear wave ultrasound elastography is lower-cost, faster, and more widely available than surgical examinations, traditional and stress radiography, magnetic resonance imaging, and computed tomographic arthrography. The data included in some preliminary reports has even showed ultrasound elastography to be more sensitive than MRI or traditional ultrasound at detecting minute changes in muscle and tendon tissue[19]. Shear wave elastography maintains many of the same benefits as traditional and stress sonography, producing the traditional B-mode images produced by those methods with the addition of color-coded elastograms and quantitative measures of shear wave velocity and Young's modulus.

There are two areas of concern with regard to the use of shear wave ultrasound elastography. A certain depth of penetration by ultrasound waves must be achieved in order for the creation of shear waves to take place, thus leading to debate over the feasibility of using shear-wave elastography for the evaluation of very superficial structures[4,47]. Admittedly, the biggest disadvantage of any of the types of ultrasound elastography, including shear wave elastography, is that they are extremely operator-dependent[37,69] This limitation is partially mitigated in shear wave elastography through the elimination of the need for consistent compression by the operator during imaging. At the present time, there is also a shortage of literature describing both the intra-rater and inter-rater reliability for the use of shear wave elastography to measure the stiffness of ligaments. Wu et al. (2016) described good to excellent ICC results for both intra- and interrater reliability when using shear wave elastography to measure the stiffness of the coracohumeral ligament[83].

There is, however, much more literature available which reports reliability statistics in musculoskeletal applications. One study on the use of shear wave elastography on the supraspinatus muscle reported an inter-examiner intraclass correlation coefficient of 0.800, and test-retest intraclass correlation coefficients of 0.700 and 0.800 for the two examiners involved in the study[64]. Another study which used shear wave elastography to measure the elasticity of the supraspinatus muscle reported intra-observer intraclass correlation coefficients between 0.945-0.970 for the four sections of the muscle examined and inter-observer intraclass correlation coefficients between 0.882 and 0.948 for the four sections of muscle[36]. Both of those studies show good to excellent reliability of shear wave elastography. A third study demonstrated fair reliability with inter-operator intraclass correlation coefficients of 0.57 and 0.56 on the first and second days of imaging the transversus abdominis[37]. Finally, a study on the elasticity of the hamstrings muscles reported intraclass correlation coefficients for three different conditions on each of four muscles and all 12 coefficients were between 0.71-0.94[45]. These results again demonstrate good-to-excellent reliability for shear wave elastography as a method for examining the elasticity of soft tissue.

Summary

The UCL is the primary stabilizer of the medial elbow, and is critical to the stability of the medial aspect of the elbow during overhead throwing motions such as the baseball pitching motion. The UCL undergoes significant stress throughout the baseball pitching motion, but especially during the last stages of the arm cocking phase and during the arm acceleration phase. The stress placed on the ligament during these phases causes the UCL to be the most commonly injured soft tissue element in the elbow of baseball pitchers. The structural properties of the medial elbow have been shown to change due to the stress of the baseball pitching motion but this study is the first to evaluate the structural properties of the UCL using sonographic imaging at regular intervals throughout a collegiate baseball season in order to examine both the acute effects of pitching bouts as well as the chronic loading of a single season on the properties of the UCL. Previous literature has used surgical observation, traditional and stress radiography, MRI, computed tomographic arthrography, and traditional and stress ultrasound to measure these changes in the UCL. The present project used ultrasound to measure changes in the structural properties of the UCL and medial elbow in collegiate baseball pitchers over the course of a season, and to examine relationships between a pitcher's recent throwing load, upper body resistance training, and perceived medial elbow stiffness with changes in the structural properties of the UCL.

METHODOLOGY

Participant Characteristics

12 NCAA Division I collegiate baseball pitchers were enrolled in this study. Demographic characteristics of the participants are listed in Table 1 for both the initial sample of participants as well as for the sample that completed the study. Three participants that initially enrolled in the study are not included in the final results. One participant withdrew and did not complete any imaging sessions after the pre-season imaging session. A second participant was excluded from the results due to researcher difficulty collecting data on that participant. Lastly a third participant was excluded after suffering a shoulder injury midseason which led him to stop all throwing for a period of time in excess of one month.

For the nine participants that completed the study and whose data is included in the results of this study, 91.76% of In-Season imaging sessions were completed on schedule (reporting for imaging session at two-week intervals) with a mean time between imaging sessions of 14.17 ± 2.51 days. Of the 72 total In-Season imaging sessions, 5 sessions were more than 18 days after the previous session, and one session was not completed at all.

Table 1. Participant Characteristics. Mean ± SD

Characteristic	Pre-Season	Post-Season
n	12	9
Throwing Arm (R / L)	10 / 2	7 / 2
Age (yr)	19.08 ± 1.24	19.11 ± 1.36
Mass (kg)	88.18 ± 5.05	88.76 ± 4.85
Height (m)	1.86 ± 0.07	1.85 ± 0.06
BMI (kg/m^2)	25.69 ± 2.43	26.02 ± 2.01
Baseball Experience (yr)	11.58 ± 2.91	11.44 ± 3.24
Pitching Experience (yr)	8.25 ± 2.63	8.44 ± 2.79

Inclusion Criteria

3. 18 - 25 years old
4. Currently-rostered NCAA Division 1 collegiate baseball pitcher

Exclusion Criteria

4. Previously diagnosed partial or complete tear of the UCL
5. Previous elbow surgery
6. Previously diagnosed abnormality of the UCL

Equipment

Two questionnaires were designed in our lab for the present research study to gather self-reported data from the participants. A demographic questionnaire was administered during the pre-season imaging questions to collect demographic and playing experience data for each participant **(Appendix A).** The second questionnaire was given to participants during each imaging session to collect self-reported data regarding their recent throwing load, treatment days with the team's athletic trainer, upper body resistance training, and perceived elbow stiffness data **(Appendix B).** Height in meters and weight in kilograms was measured using a Seca 703 digital scale (Seca gmbn & Co.kg, Hamburg, Germany).

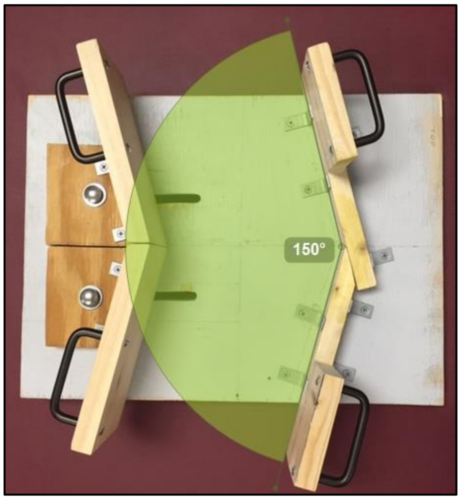


Figure 5. ***Arm Position Splint*** Adjustable-width arm position splint which is used to support the participants' arms and stabilize them at 30° of elbow flexion.

During the ultrasound imaging, participants' arms were placed in an adjustable-width arm position splint. The splint was designed to stabilize the participant's arm in 30° of elbow at the elbow (*Figure 5*). B-mode ultrasound images were collected using a Supersonic Aixplorer MultiWave SSIP90029 (SuperSonic Imagine, S.A., Aix-en-Provence, France). Imaging was performed using a SuperLinear™ SL15-4 musculoskeletal transducer (SuperSonic Imagine, S.A., Aix-en-Provence, France). Measurements were calculated on images from the ultrasound machine using a custom MATLAB (MathWorks, Natick, MA, USA) image processing suite designed in the East Carolina University Biomechanics Laboratory. After measurements were taken, all data was stored using Microsoft Excel (Microsoft, Redmond, WA, USA).

Experimental Procedure

Potential participants expressed their interest in taking part in the present research study during a team meeting in which the project was explained to the pitching staff. The researcher then contacted interested participants individually and scheduled them for their pre-season imaging session. All research was conducted in the East Carolina University Biomechanics Lab.

Prior to beginning the pre-season imaging session, participants arrived in the Biomechanics Lab and read and signed the Informed Consent Document **(Appendix C)**. Participants also completed both the demographic questionnaire and the recent throwing load questionnaire before having their height and weight measured and recorded. The questionnaire regarding recent throwing load asked participants to report various recent workload metrics as well as to answer several questions regarding their perceived elbow stiffness at various points since the last imaging session. The questions were answered on a 1-5 scale using the answers "Strongly Disagree, Disagree, Neither, Agree, and Strongly Agree." The last question, regarding whether or not the participants felt that their throwing and game availability had been limited by elbow stiffness, was phrased as a false negative question. After completing the questionnaires, participants were asked to lay supine on a treatment table with their right arm towards the Aixplorer ultrasound unit in order to begin the imaging session.

The participant's arm was guided by the researcher into the adjustable-width arm position splint to be positioned properly for imaging. The splint was adjusted to properly fit the width of the arm and then secured by locking the sliding pieces in place and placing neoprene straps over the top of the splint. The researcher positioned the wrist in a neutral position with respect to pronation and supination, and explained to the participant to maintain that neutral position. In the Supported condition, the upper arm and forearm were both placed directly on, and supported by, the base of the adjustable-width arm position splint. In the Elevated-Unstressed condition, the participant's upper arm was elevated using a piece of foam in order to allow gravity-stressed ulnohumeral gapping to occur. Participants were also given a piece of Styrofoam to hold in their right hand to mimic the shape of the 1-kg weight that they would be given in the Elevated-Stressed condition. Participants were asked to loosely hold the foam as opposed to squeezing it, and to allow their wrist to naturally fall into extension to prevent muscle-guarding. In the Elevated-Stressed condition, the participant's upper arm was also elevated using a piece of foam in order to allow for ulnohumeral gapping. Participants were given a 1-kg weight to hold in their right hand to cause valgus-stressed ulnohumeral gapping. Participants were again asked to loosely hold the weight as opposed to squeezing it, and to allow their wrist to naturally fall into extension to prevent muscle-guarding.

Ultrasound imaging of the UCL was performed with the participant's arm in each of three conditions: 1) Supported, 2) Elevated-Unstressed, and 3) Elevated-Stressed. In each of the three conditions, imaging was completed with the ultrasound probe oriented parallel to the axis of the anterior bundle of the UCL (*Figure 6*).Three successful B-mode ultrasound images were recorded in order to measure the length, thickness, and space of the UCL, as well as the U-H gap. Images were considered successful based on the ability to visualize the medial epicondyle and trochlea of the humerus, the coronoid process of the ulna, and the anterior bundle of the UCL (*Figure 7*).

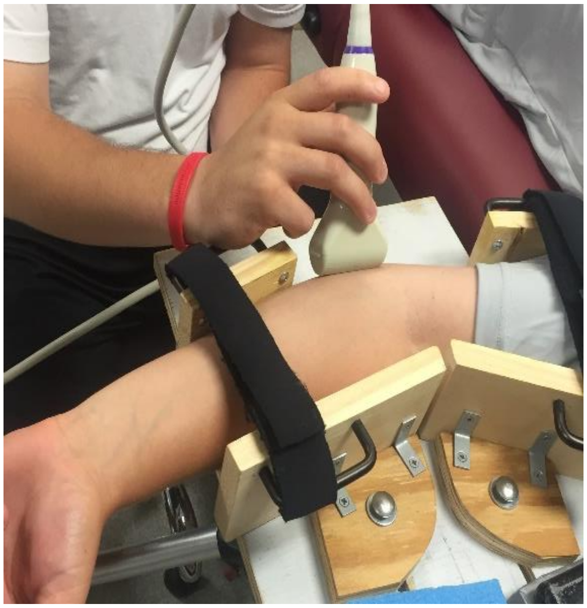


Figure 6. ***Ultrasound Probe Orientation***
The axis of the ultrasound probe was oriented parallel to the axis of the participant's forearm in order for imaging of the UCL.

Bilateral imaging was performed bilaterally in each of the three conditions during the Pre-Season imaging session. Imaging was always performed on the right elbow first, and then the left regardless of which arm was the participant's throwing arm during bilateral imaging sessions. In-Season imaging sessions were scheduled every two weeks, beginning approximately one month prior to the first scheduled game. These collections were considered In-Season because the players were participating in full practices daily, throwing regular bullpen sessions, and pitching in scrimmages. In the event that a participant was

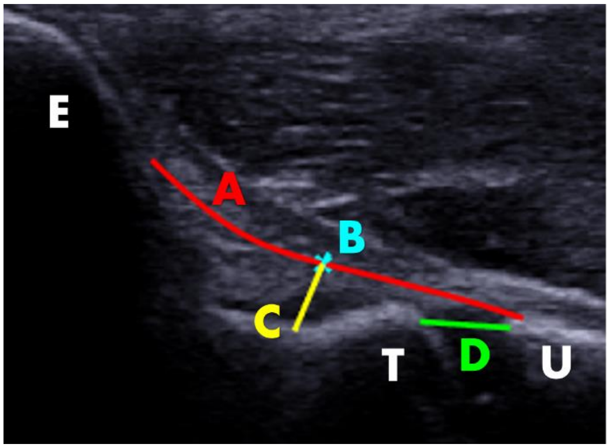


Figure 7. ***Analyzed B-Mode Image of the UCL***
B-mode ultrasound image showing the structural properties of the UCL. A) UCL Length B) UCL Thickness C) UCL Space D) Ulnohumeral Gap, E) Medial epicondyle of the humerus, T) Trochlea of the humerus, U) Proximal head of the ulna.

unable to complete an In-Season imaging session according to their biweekly schedule the session was rescheduled and completed within one week of the originally scheduled time, and then the participant returned to their normal imaging schedule. During each In-Season imaging session, the participant completed the recent throwing load questionnaire and had their height and weight recorded before proceeding with the ultrasound imaging. The procedure for In-Season imaging was the same as that used in the Pre-Season imaging session, although the imaging was only performed on the participant's throwing arm. Post-Season imaging sessions were collected within one week of the conclusion of the collegiate baseball regular season. After completing the recent throwing load questionnaire, imaging was again performed bilaterally following the same procedure as the Pre-Season sessions in order to evaluate whether or not any changes had occurred to the UCL in the participant's non-throwing arm.

Data Reduction

Demographic data and throwing load and perceived stiffness data from the demographic questionnaire and the recent throwing load questionnaire were recorded in Excel after each participant completed the questionnaire. After imaging was completed, recorded B-Mode images were exported as DICOM files as well as .jpg images. All images were then processed in MATLAB using an image processing suite created in the East Carolina University Biomechanics Laboratory. The image processing suite calculated the Euclidean distance between user-selected points on the image marking the boundaries of each measurement. Values for UCL length, UCL thickness, UCL space, and U-H gap were measured on the B-Mode ultrasound images. With the exception of UCL Thickness in the Supported and Elevated-Unstressed Condition, the primary researcher displayed Good to Excellent reliability for measuring the structural properties of the

UCL using ultrasound imaging. Table 2 shows the present researcher's reliability for structural property measurements of the UCL from B-Mode ultrasound images taken using the Aixplorer machine. These results are from a separate sample of 10 healthy, non-overhead throwing athletes between the ages of 18-25, collected on separate days within a seven-day timespan.

Table 2. Primary Researcher Reliability. ICC 2.K Values (SEM in mm)

UCL Property	**Imaging Condition**		
	Supported	**Elevated - Unstressed**	**Elevated - Stressed**
UCL Length	0.889 (0.58)	0.889 (0.61)	0.908 (0.58)
UCL Thickness	0.210 (0.11)	0.222 (0.10)	0.830 (0.04)
UCL Space	0.753 (0.44)	0.834 (0.41)	0.889 (0.37)
Ulnohumeral Gap	0.911 (0.25)	0.944 (0.20)	0.939 (0.21)

The way in which each structural property was measured is displayed in *Figure 7.* UCL length was measured along the path of the anterior bundle of the UCL from the origin of the ligament on the medial epicondyle of the humerus to its insertion on the ulnar tubercle. UCL thickness was measured as the width of the ligament at 50% of its length. UCL space was measured as the distance from the surface of the humerus in the trough between the medial epicondyle and the trochlea, to the midpoint of the UCL thickness at 50% of the length of the ligament. UCL Space was calculated perpendicular to the tangent line at 50% of the length of the UCL. Ulnohumeral gap was measured as the distance from the most distal aspect of the trochlea of the humerus to the most proximal aspect of the head of the ulna.

Statistical Analysis

Several different statistical tests were performed on the data involved in the current research. A 2x2 ANOVA (time by arm side) was performed to test for significant differences in the bilateral Pre-Season and Post-Season imaging data. Percent difference from Pre-Season measurements were calculated for each of the outcome measures at each in-season imaging session in order to track UCL properties throughout the season, and paired sample t-tests were performed to evaluate differences between biweekly imaging sessions for both the raw values and percent change from pre-season. Correlations between throwing load/perceived elbow stiffness and measured changes in the properties of the UCL were identified using the Pearson product-moment correlation.

RESULTS

The primary purpose of this study was to examine changes in the structural properties of the UCL in collegiate baseball pitchers over the course of a season. This chapter will review the results of the present study pertaining to changes seen in the structural properties in the participants' throwing arms over the course of the season, and bilateral differences in the participants' post-season measurements compared to their pre-season measurements. This chapter will also review results pertaining to the second purpose: determining if relationships exist between several self-reported variables with any changes in the structural properties of the UCL.

UCL Structural Properties throughout the Season

Mean values for UCL length, UCL thickness, UCL space, and U-H gap throughout the season in each condition can be seen in Figure 8. The mean percent change values for the entire season for UCL length were -5.33 ± 5.07%, -6.27 ± 4.89%, and -8.72 ± 5.48% for the Supported, Elevated-Unstressed, and Elevated-Stressed conditions, respectively. The mean percent change values for UCL thickness were -4.69 ± 9.52%, -2.29 ± 10.74%, and -6.12 ± 11.86% for the Supported, Elevated-Unstressed, and Elevated-Stressed conditions, respectively. The mean percent change values for UCL space were 1.70 ± 27.95%, 4.36 ± 18.96%, and 1.55 ± 20.95% for the Supported, Elevated-Unstressed, and Elevated-Stressed conditions, respectively. Finally, the mean percent change values for U-H gap were 14.25 ± 21.87%, -2.24 ± 11.33%, and -3.62 ± 9.25% for the Supported, Elevated-Unstressed, and Elevated-Stressed conditions, respectively. Variation between bi-weekly imaging sessions in mean percent difference from pre-season values for each of the four structural properties in each of the three imaging conditions can be seen in Figure 9.

There were no trends in significant changes from pre-season throughout the season in participants' throwing arms for any of the four structural UCL properties measured in the present study, although a noticeable increase can be seen in U-H gap in the supported condition towards the beginning of the in-season imaging sessions, and a decrease can be seen for UCL length in all three imaging conditions from the pre-season imaging session to the first in-season session.

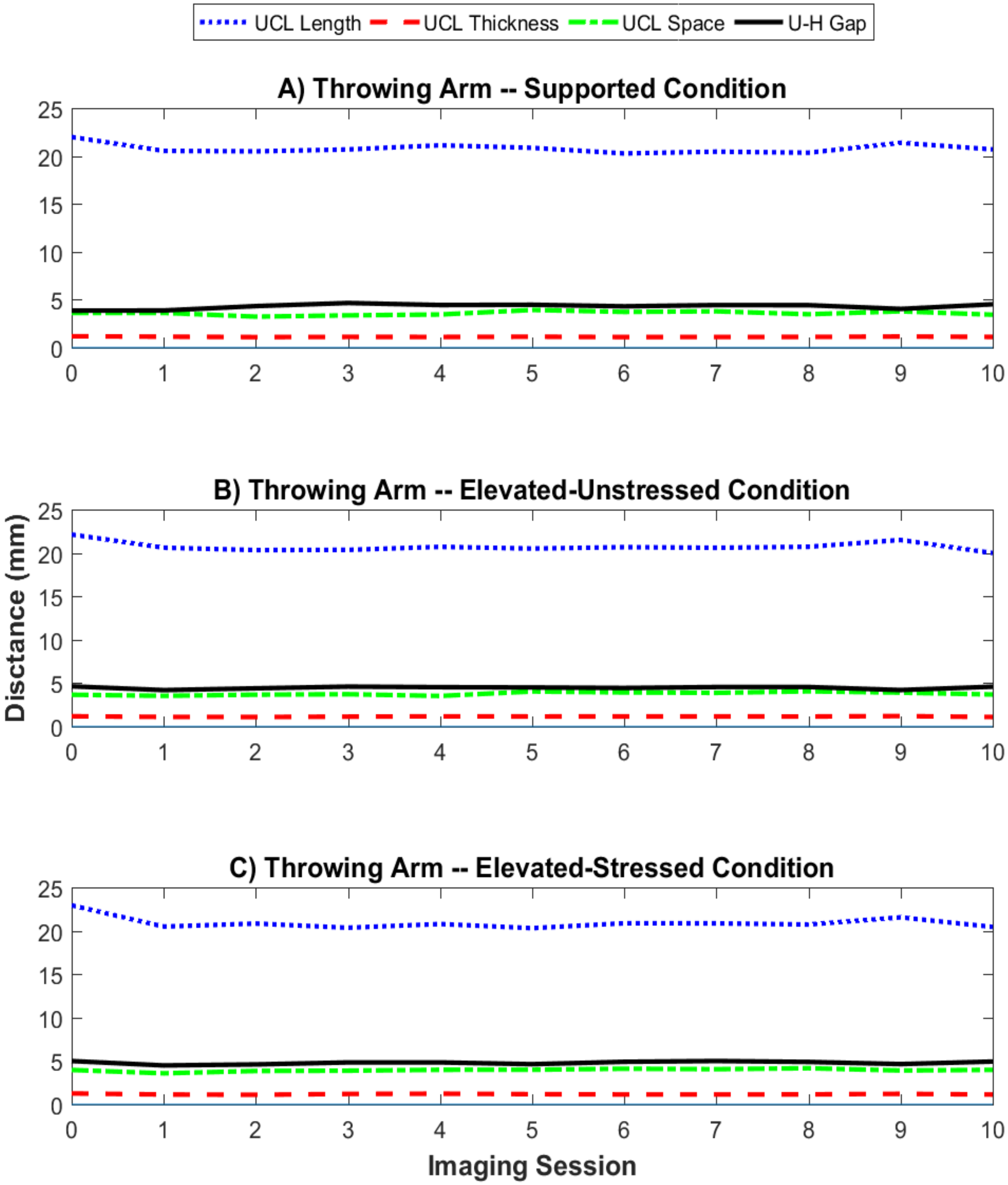


Figure 8. ***UCL Structural Properties throughout a Collegiate Baseball Season***

Longitudinal measurements for UCL Length, UCL Thickness, UCL Space, and U-H Gap for participants' throwing arms in each of the three imaging conditions: A) Supported, B) Elevated-Unstressed, and C) Elevated-Stressed.

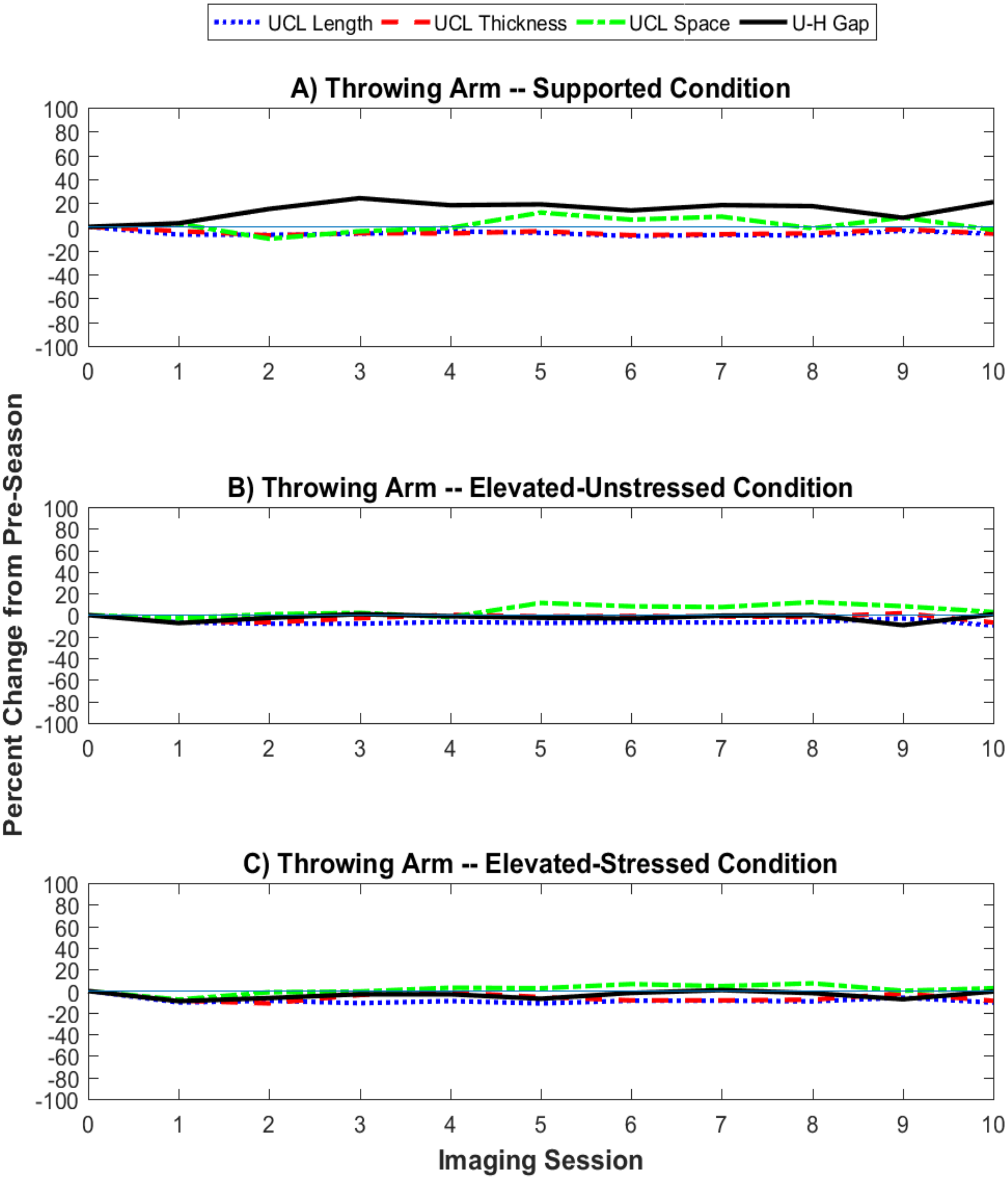


Figure 9. ***Change in UCL Structural Properties throughout a Collegiate Baseball Season***

Percent change from pre-season measurements for UCL Length, UCL Thickness, UCL Space, and U-H Gap for participants' throwing arms in each of the three imaging conditions: A) Supported, B) Elevated-Unstressed, and C) Elevated-Stressed.

Bilateral Pre-Season and Post-Season Differences

Pre- and Post-Season bilateral mean values for each of the structural properties are shown in Table 3. Results indicated main effects for throwing vs non-throwing arm in the Elevated-Unstressed condition showing a greater UCL space in the throwing arm ($p = 0.012$), and in the Elevated-Stressed condition for UCL Thickness and UCL space ($p = 0.034$, $p = 0.002$), again showing significantly greater measurements in the throwing arms of our participants. There were also several main effects for time, each demonstrating significant decreases in the properties being measured. The 2x2 ANOVA demonstrated a main effect for Pre- vs Post-season in the Supported condition for UCL length and UCL thickness ($p = 0.001$, $p = 0.048$), in the Elevated-Unstressed condition for UCL length ($p < 0.001$), and in the Elevated-Stressed condition for UCL length and UCL thickness ($p < 0.001$, $p = 0.008$). Plots displaying main effects for arm and time can be seen in Figure 10. There were no interaction effects for any of the four structural properties in any of the three conditions.

Table 3. Bilateral Structural Property Differences. Mean ± SD

		Throwing Arm		Non-Throwing Arm		Time-Arm Interaction p-value
Supported		Pre-Season	Post-Season	Pre-Season	Post-Season	
	UCL Length[b]	22.16 ± 1.16	20.81 ± 1.09	21.58 ± 1.24	20.37 ± 1.60	0.747
	UCL Thickness[b]	1.18 ± 0.07	1.11 ± 0.07	1.14 ± 0.11	1.09 ± 0.08	0.620
	UCL Space	3.65 ± 0.54	3.41 ± 0.68	3.09 ± 0.63	3.09 ± 0.79	0.925
	U-H Gap	3.94 ± 0.92	4.32 ± 0.76	3.95 ± 0.61	4.04 ± 0.65	0.482
Elevated-Unstressed		Throwing Arm		Non-Throwing Arm		Time-Arm Interaction p-value
		Pre-Season	Post-Season	Pre-Season	Post-Season	
	UCL Length[b]	22.19 ± 0.89	19.97 ± 0.92	21.69 ± 1.36	19.69 ± 1.14	0.801
	UCL Thickness	1.19 ± 0.11	1.10 ± 0.08	1.14 ± 0.08	1.12 ± 0.07	0.234
	UCL Space[a]	3.67 ± 0.60	3.54 ± 0.78	3.10 ± 0.60	2.91 ± 0.51	0.917
	U-H Gap	4.74 ± 1.03	4.62 ± 0.79	4.31 ± 0.97	4.32 ± 0.82	0.827
Elevated-Stressed		Throwing Arm		Non-Throwing Arm		Time-Arm Interaction p-value
		Pre-Season	Post-Season	Pre-Season	Post-Season	
	UCL Length[b]	23.01 ± 1.11	20.52 ± 1.12	22.02 ± 1.39	19.67 ± 1.48	0.881
	UCL Thickness[a,b]	1.26 ± 0.13	1.12 ± 0.06	1.14 ± 0.05	1.10 ± 0.09	0.152
	UCL Space[a]	3.95 ± 0.80	3.77 ± 0.57	3.23 ± 0.64	2.98 ± 0.53	0.879
	U-H Gap	5.08 ± 0.91	4.97 ± 0.80	4.64 ± 0.87	4.38 ± 0.74	0.808

[a] Main effect for Arm, [b] Main effect for Time

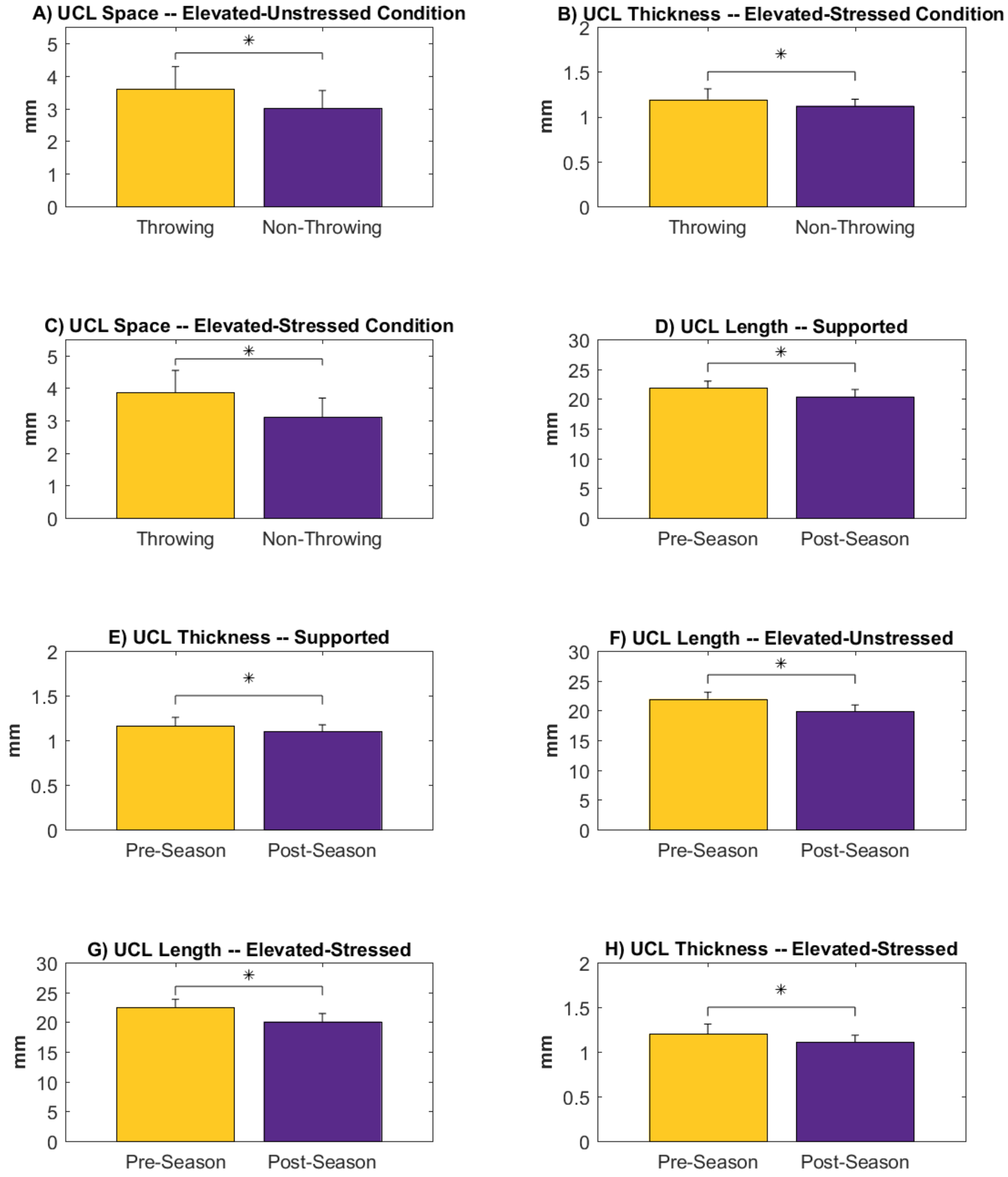


Figure 10. ***Main Effects.*** **denotes statistical significance (p < 0.05)*
Arm x Time ANOVA results showing a main effect for arm for A) UCL space in the Elevated-Unstressed condition, and for B) UCL thickness and C) UCL space in the Elevated-Stressed condition, and a main effect for time for D) UCL length and E) UCL thickness in the Supported condition, for F) UCL length in the Elevated-Unstressed condition, and for G) UCL length and H) UCL thickness in the Elevated-Stressed condition.

Relationships between Recent Workload and Changes in UCL Properties

Significant correlations are shown in Table 4. Number of days between imaging sessions showed a weak, negative correlation with changes in the U-H gap in the Supported condition ($r = -0.20$, $p = 0.05$). The amount of innings thrown in games or scrimmages by participants showed a moderate, positive correlation with changes in the thickness of the UCL in the Elevated-Stressed condition ($r = 0.42$, $p < 0.01$). The number of bullpen sessions thrown between imaging sessions showed a weak, negative correlation with changes in the length of the UCL in the Supported condition ($r = -0.23$ $p = 0.03$). The proximity of participants' most recent upper body resistance training session showed a weak, positive correlation with changes in the UCL Space in the Elevated-Unstressed condition ($r = 0.14$, $p = 0.20$). Finally, the number of days that participants sought treatment from team medical personnel for "elbow stiffness" showed a weak, positive correlation with changes in the length of the UCL in the Supported condition ($r = 0.39$, $p < 0.01$).

Relationships between Perceived Elbow Stiffness and Changes in UCL Properties

There were no significant relationships between perceived elbow stiffness and changes in any of the UCL structural properties. The frequency at which participants experienced elbow stiffness while throwing was most closely correlated with changes in the UCL space in the Elevated-Stressed condition ($r = -0.33$ $p < 0.01$). The frequency with which participants experienced elbow stiffness after finishing a throwing session was most closely correlated with changes in UCL space in the Supported condition ($r = 0.38$ $p < 0.01$). Experiencing elbow stiffness while performing activities of daily living was also most closely correlated with changes in UCL space in the Elevated-Stressed condition ($r = 0\text{-}0.34$ $p < 0.01$). Whether participants perceived that they had had an increase in elbow stiffness since the last imaging session was most closely correlated with changes in the U-H gap in the Elevated-Unstressed condition ($r = -0.37$ $p < 0.01$). Lastly, whether or not participants felt their throwing and game availability had been limited by elbow stiffness since the last imaging session was moderately correlated with changes in the U-H gap in the Supported condition ($r = 0.50$, $p < 0.01$).

Table 4. ***Significant Correlations Between Questionnaire Responses and Changes in UCL Properties***

	Supported Condition				**Elevated - Unstressed Condition**				**Elevated-Stressed Condition**			
	Length	Thickness	Space	Gap	Length	Thickness	Space	Gap	Length	Thickness	Space	Gap
Days Between[a]	--	--	--	*-0.20*	--	--	--	--	--	--	--	*-0.18*
Innings Thrown[b]	--	**-0.22**	**0.27**	*0.21*	*-0.18*	--	--	--	**0.30**	**0.42**	*0.20*	--
Bullpens[c]	**-0.23**	--	--	--	--	--	--	--	--	--	--	--
Days Since UB Lift[d]	--	--	--	--	--	--	--	--	--	--	--	--
Treatment Days[e]	**0.39**	--	--	--	--	--	*-0.20*	--	--	**-0.21**	**-0.30**	--
Stiff During[f]	--	--	--	**0.22**	**-0.22**	--	**-0.22**	**-0.29**	--	--	**-0.33**	--
Stiff After[g]	--	--	**0.38**	**0.34**	**-0.35**	--	**-0.32**	**-0.25**	--	--	**-0.26**	--
Stiff ADL[h]	--	--	--	--	--	--	**-0.25**	**-0.32**	--	--	**-0.34**	--
Increase Stiffness[i]	**0.21**	--	**0.24**	--	*-0.20*	--	--	**-0.37**	--	--	**-0.29**	*-0.19*
Not Limited by Stiffness[j]	**0.31**	--	**0.28**	**0.50**	--	--	--	**0.27**	--	--	--	--

p < 0.05 *0.05 < p < 0.10*

[a] Days between imaging sessions, [b] Innings throwin in games or scrimmages since last imaging session, [c] Number of bullpen sessions thrown since last imaging session, [d] Number of days since last upper-body strength training session, [e] Number of days since last imaging session that participant sought treatment for "elbow stiffness", [f] Participant regularly experiences elbow stiffness while throwing, [g] Participant regularly experiences elbow stiffness after throwing, [h] Participant regularly experiences elbow stiffness while performing daily activities, [i] Participant feels as though they have had an increase in elbow stiffness since last imaging session, [j] Participant's game availability and throwing have not been limited by elbow stiffness

Summary

The structural properties of the UCL, including UCL length, UCL thickness, UCL space, and U-H gap, did not display any significant changes between bi-weekly imaging sessions throughout a single collegiate baseball season. Considering differences in the pre- and post-season imaging sessions, main effects for time were seen demonstrating decreases in UCL length and UCL thickness from pre- to post-season in various conditions and main effects for arm demonstrating increased UCL space and UCL thickness in various conditions for the throwing arm compared to non-throwing arm. The results of this study did not display any interaction effects for any of the four structural properties in any of the three conditions when evaluating bilateral means from the pre- and post-season imaging sessions. There were several weak to moderate correlations between recent workload or perceived elbow stiffness metrics and changes in any of the UCL structural properties.

DISCUSSION

The two purposes of the present research were to examine changes in the structural properties of the UCL and medial elbow in NCAA Division I collegiate baseball pitchers over the course of a season, and to determine if relationships exist between recent throwing load, upper body resistance training, and perceived medial elbow stiffness with any observed changes in the structural properties of the UCL and medial elbow. This chapter is divided into the following sections: 1) Development of Research Significance, 2) Discussion of Results, 3) Limitations, and 4) Conclusions.

The continued rise in significant injury to the UCL in baseball pitchers throughout the past twenty years has driven the need to better understand the mechanism and risk factors of such injuries, as well as the need to develop a practical technique for monitoring a pitcher's UCL during the season to determine if an individual is at an elevated risk of injury[28,61]. The effect of the overhead throwing motion used in baseball pitching on the structural properties of the UCL in the throwing arms is well documented[12,52,56]. A majority of the research attempting to evaluate risk factors for pitching injuries has been conducted in youth and adolescent pitchers, and their findings suggest these changes and injuries to the soft-tissue structures of the throwing arm, including the UCL, to be the result of cumulative pitching workload, and not acute injuries[28,61]. It is of note that at the Major League level, no cumulative workload or pitching schedule metric was determined to be a significant predictor of future injury in one of the few studies examining the relationship between workload/pitching schedule and injury risk[42]. Further examining distinctions in the biomechanics and injury risk of baseball pitchers based on competition level, a study conducted at the American Sports Medicine Institute reported that the mechanics of the pitching motion did not significantly change between a sample of youth, high school, collegiate, and professional baseball pitchers. The authors did, however, report significant differences in all eight kinetic parameters that were examined in the study and ultimately concluded that the greater elbow varus torque and elbow extension velocity generated in collegiate and professional pitchers may place pitchers at these competition levels at an increased risk for a litany of arm injuries including tears of the UCL and valgus extension overload in the elbow[30].

The differences in previous literature findings based on level of play highlight the need for continued research aimed at better understand the mechanism and risk factors of injuries to the UCL in baseball pitching, as well as the need to develop a practical technique for monitoring a pitcher's UCL. Additionally, these differences between competition levels also justify the selection of a sample of collegiate baseball pitchers for the present study as recent research has often examined adolescent and high school pitchers, or professional players, and it cannot be assumed that findings from such research will translate to collegiate baseball pitchers.

There is a scarcity of research examining longitudinal changes in UCL properties in baseball pitchers. A recent study by Keller et al. (2015) compared the structural properties of the UCL pre- and post-season in a sample of high school pitchers and found a significant increase in UCL space and a non-significant increase in ulnohumeral gap from pre- to post-season, however tracking these properties of the ligament at regular time intervals throughout a single season, and relating changes in those properties to cumulative workload as done in the current study is novel. Another novel aspect of the present project was examining relationships between changes observed and participants' recent throwing load, the timing of their most recent upper body resistance training, and perceived elbow stiffness during various activities with changes in UCL structural properties. Determining if relationships are present between these workload and perceived stiffness variables and changes in the UCL, in conjunction with continued research, has the potential to assist coaches in designing training regimens and throwing protocols, and aid medical personnel working with pitchers to prevent overstressing the ligament at times when the UCL may be the most susceptible to injury.

Discussion of Results

UCL Length in Division I Collegiate Baseball Pitchers: The results from our research for the length of the UCL in collegiate baseball pitchers are approximately 10% shorter than those previously reported by Bica et al. (2015) in both a gravity-stressed and a valgus-loaded condition (24.4 ± 2.0 mm[6] vs 22.19 ± 0.89 mm, and 25.9 ± 1.8 mm[6] vs 23.01 ± 1.11 mm). At the conclusion of the regular season, throwing arm UCL length measured 19.97 ± 0.92, and 20.52 ± 1.12 mm in the Elevated-Unstressed, and Elevated-Stressed conditions, respectively. There is no literature currently reporting UCL length pre- and post-season in collegiate baseball pitchers. Further research is needed to determine whether or not our measurements are reasonable and representative of the population.

Some of the difference in the lengths of the UCL reported in this research compared to those from Bica et al. may be attributable to differences in how the origin and insertion of the UCL were defined, and subsequently identified during the individual research studies, as well as differences in using a linear measurement compared to the non-linear trace of UCL length used in our research (*Figure 11)*. It is not uncommon for ultrasound equipment, including that in our own lab, to be restricted to taking straight-line length measurements. As soft tissue structures such has the UCL often follow a curvilinear path from origin to insertion in the body, using image processing software such as Osirix (Pixmeo, Geneva, Switzerland) or the our lab's image processing suite designed in Matlab are essential for the accuracy of tracing and measuring the length of soft-tissue structures in imaging studies such as this.

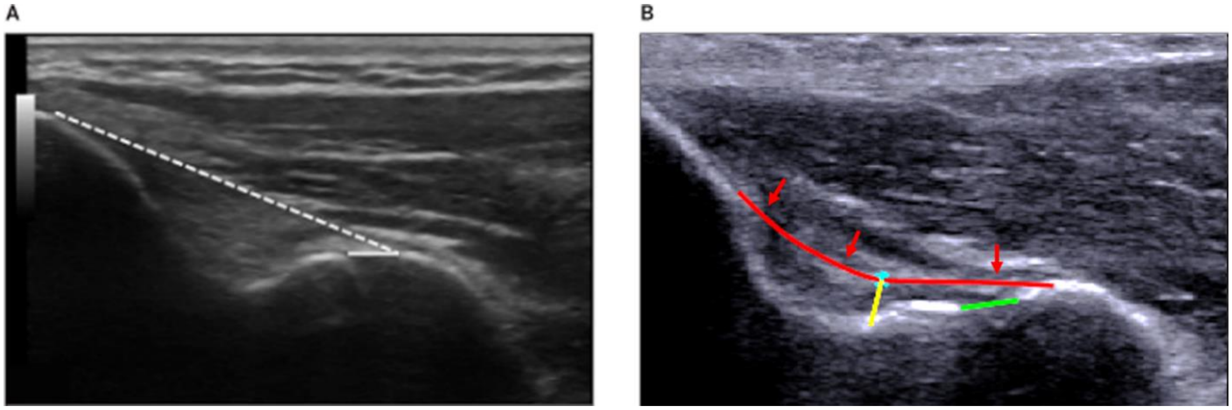


Figure 11. ***UCL Length Measurement Methodology***
Images displaying how UCL length measurements were performed in A) Bica et al. 2015, and B) the current research.

UCL Thickness in Division I Collegiate Baseball Pitchers: Measuring UCL thickness as the thickness of the ligament only is a recent shift in the literature and has only been reported twice previously (see *UCL Space in Division I Collegiate Baseball Pitchers*). Additionally, previous literature has only reported UCL thickness measurements in a valgus-loaded condition. The pre-season UCL thickness values from the present research were smaller than those previously reported in two 2015 papers from a group at Henry Ford Hospital on samples of 22 high school pitchers, (1.85 ± 0.51 mm[52], 1.85 ± 0.51 mm[43] vs 1.18 ± 0.07 mm).

Our values for UCL thickness the Elevated-Stressed condition were also smaller at the conclusion of the season than the post-season values reported in the research by Keller et al. (2015) in a valgus-loaded condition (2.20 ± 0.71 mm[43] vs 1.12 ± 0.06 mm). The results of our research do not confirm the significant increase seen in UCL thickness in the study by Keller et al. (2015).

The differences between the UCL thickness measurements in the present research and those reported by Keller (2015) and Marshall (2015) are most likely attributable to differences in defining the UCL thickness measurement between the experimenters responsible for taking measurements in the two studies and the positioning of the research participants during the imaging sessions. Additionally, a major methodological difference between the imaging reported on in 2015 by both Marshall et al. and Keller et al., and the present research was the positioning of participants during imaging sessions and the modality used to apply the valgus load to the elbow. In the prior studies, imaging was performed with participants seated upright, with the throwing shoulder in a position of maximum external rotation and a valgus load manually applied by an examiner until there was resistance to joint movement. In the present research, participants laid supine on a treatment table and the valgus load was applied using a standard 1-kg weight placed in participants' hands. While it is reasonable to not expect any significant effects, it is unknown what role the difference in body positions and method of loading may play in the structural properties of the UCL. The differences in methodologies may act to exaggerate any differences that may have already been present between the studies due to the most significant limitation of sonographic imaging, being that ultrasound imaging is extremely evaluator-dependent.

UCL Space in Division I Collegiate Baseball Pitchers: The values from our research for UCL space in the throwing arms of baseball pitchers are much smaller than those previously reported. Some authors have previously referred to our measurement of UCL space as UCL thickness[12,56]. Marshall et al. (2015) highlight this by differentiating their measurements of our UCL Space as "Nazarian thickness" and their measurement of our UCL thickness as "ligament-only thickness." The pre-season UCL space measurements from our research are much smaller than those reported previously in the throwing arms of baseball pitchers in both a supported (6.15 ± 1.57 mm[12], 6.54 ± 0.83 mm[52], and 6.3 ± 1.0 mm[56] vs 3.65 ± 0.54 mm), and a valgus-stressed condition (6.3 ± 1.4 mm[56] vs 3.95 ± 0.80 mm).

It should be noted that the UCL space measurements in the prior studies described above were not from samples of collegiate baseball pitchers, as the results from Ciccotti et al. (2014) and Nazarian et al. (2003) were from samples of professional baseball players, while the results from Marshall et al. (2015) were from a sample of high school pitchers. The difference in age, level of competition, and years of pitching experience may play a factor in the difference between those results and the results of this study. Additionally, it appears that the "mid-point" used to measure UCL space in the current study was located distal to that in the previous studies referenced above (*Figure 12*). The UCL space measurement previously reported was also measured as a vertical line, while the UCL space measurement in our research was standardized to be perpendicular to the path of the ligament at the midpoint of UCL length. This distal shift in the measurement of UCL would lead to a smaller measurement of UCL space as the bony surface of the distal humeral trough is closer to the ligament than that at the deepest point of the trough. This distal shift may be attributed to differences in the definition and subsequent identification of the origin of the UCL in the present study compared to that reported in prior studies as discussed previously.

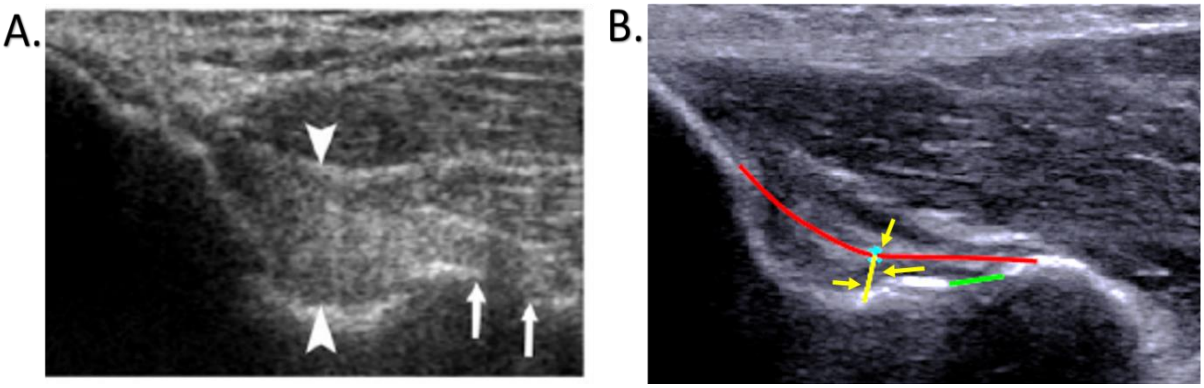


Figure 12. ***UCL Space Measurement Methodology***
Images displaying how UCL length measurements were performed in A) Nazarian et al. 2003, and B) the current research.

The study by Ciccotti et al. describes a 10-year study in which stressed ultrasound was performed once per year on a sample of professional baseball pitchers during the pre-season examinations upon arrival at spring training. One major difference between Ciccotti et al. and the present research is the method used to create the external valgus elbow torque during imaging sessions. A Telos machine (Telos, Marburg, Germany) is a device that stabilizes the arm at the shoulder and wrist and can mechanically apply very precise valgus loads at the elbow. Ciccotti and colleagues used a Telos machine to apply 150 N of external valgus loading directly on the lateral side of the elbow (*Figure 13*). While the force was applied at the elbow in the studies using the Telos machine, the valgus torque at the elbow would still be created near the wrist where the forearm is stabilized in the machine, similar to the creation of the valgus force near the hand/wrist in our study. That being said, the valgus torque applied in our research was likely much lower than that in the studies by Nazarian and Ciccotti. Additionally, it is unknown how much of the force applied by the Telos machine was applied as an external valgus torque at the elbow as opposed to being applied forces at the shoulder. The difference in force and location may not have dramatically impacted the comparability of the results to those of this study. An additional difference is that the longitudinal aspect of their study was performed through one imaging session per professional baseball season, while the longitudinal aspect of our research was performed via biweekly imaging sessions within a single collegiate baseball season.

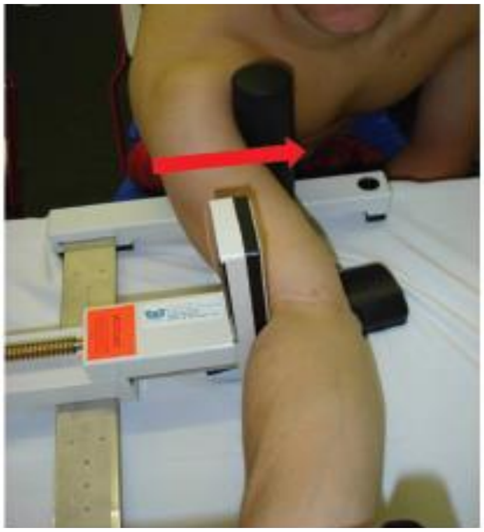


Figure 13. Telos Machine
Experimental set-up involving the Telos Machine (Ciccotti et al. 2014).

At the conclusion of the regular season, UCL space in the throwing arm measured 3.41 ± 0.68, 3.54 ± 0.78, and 3.77 ± 0.57 mm in the Supported, Elevated-Unstressed, and Elevated-Stressed conditions, respectively. There is no literature presently available reporting the change in UCL space measurement from pre- to post-season in either the throwing or non-throwing arms of baseball pitchers. UCL space demonstrated a main effect for arm indicating a larger UCL space in the pitchers throwing arm than non-throwing arm in both the Elevated-Unstressed and Elevated-Stressed conditions. Additional research is needed to validate the decreases seen in the present research from pre- to post-season, as well as to further determine the acute effects of a single season of pitching on UCL space.

U-H Gap in Division I Collegiate Baseball Pitchers: Compared to the values reported in the literature for U-H gap in throwing arms of baseball pitchers using sonographic imaging, the results of this study tended to be slightly larger. This trend was seen at rest (3.32 ± 0.07 mm[12,56], 2.8 ± 1.0 mm[56], vs 3.94 ± 0.92 mm), with the application of a gravity stress (3.13 ± 0.70 mm[43], 3.13 ± 0.70 mm[52], 4.0 ± 0.9 mm[6] vs 4.74 ± 1.03 mm), and with an applied valgus stress (3.87 ± 1.03 mm[43], 3.87 ± 1.03 mm[52], 4.56 ± 1.10 mm[12,56], 4.2 ± 1.5 mm[56], 5.3 ± 1.1 mm[6] vs 5.08 ± 0.91 mm). It is important to consider both the method and amount of valgus torque applied when comparing results of U-H gap as those two factors may play a large role in the results of the imaging. Our research used a 1-kg weight placed in participants' hands to apply a valgus torque at the elbow. Bica et al. (2015) applied a valgus torque to the elbow by placing the wrist under a 25 N load. Ciccotti et al. (2014) applied a 150 N force from the lateral side of the elbow using a Telos machine to create a valgus stress at the elbow. The studies by Nazarian et al. (2003), Marshall et al. (2105), and Keller et al. (2015) all used manual valgus loading by an examiner. The slightly larger U-H gap measurements in the present research compared to those in the studies by previous authors may be a result of the valgus torque applied at the elbow by the weight placed in the participants' hand as opposed to a load applied by an examiner, as well as the development of finer imaging technology in recent years allowing for more precise bony surfaces[43,52,56].

These values from sonographic imaging are confirmed as reasonable by two studies using Telos machines, similar to that used by Ciccotti (2014), to apply valgus torque at the elbow during radiographic imaging sessions. Radiographic imaging was performed on 136 male collegiate athletes from various sports reported U-H gap measurements on the athletes' dominant side of 3.60 ± 0.98 mm and 4.61 ± 1.14 mm at rest and with the application of 130N of valgus stress. There were not any significant differences in U-H gap measurements based on whether or not the athlete was involved in an overhead-throwing sport, although the increase with the application of the valgus stress in the throwing arm compared to non-throwing arms was largest in the baseball players in this sample[71]. In a second radiographic imaging study, mean values for U-H gap in the throwing arms of 40 professional baseball pitchers were reported to be 3.53 ± 0.59 mm and 4.72 ± 1.23 mm at rest and with the application of 150N of valgus stress using the Telos machine[22]. These measurements indicate that the U-H gap values reported in our research are reasonable as they vary 8-12% from the means reported using radiographic imaging, which has been used for more than 20 years to evaluate laxity of medial elbow structures.

Post-season measurements for U-H gap in the throwing arm during the Elevated-Unstressed and Elevated-Stressed conditions were larger than those reported by Keller and colleagues in 2015 (Elevated-Unstressed: 3.87 ± 1.03 mm[43] vs 4.62 ± 0.79 mm, Elevated-Stressed: 4.30 ± 1.16 mm[43] vs 4.97 ± 0.80 mm). This difference could be attributed to the effect of additional years of pitching experience by the time that the pitchers were in college (Current sample = 19.11

years) compared to high school-aged pitchers (16.9 years[43]). Additionally, the pre- to post-season changes seen in this study (Elevated-Unstressed: -0.12 mm vs +0.20 mm, Elevated-Stressed: -0.11 mm vs +0.43 mm) were contrary to those reported by Keller.

These differences may have been a result of the difference in defining *post-season* imaging sessions. The post-season imaging sessions performed by Keller et al. were completed within eight days of their final game of that particular season. In our research, the “post-season” imaging sessions were performed after the conclusion of the collegiate regular season, however this was within a three day period between the team’s final regular season series and the beginning of the conference post-season tournament. As such, the players were still preparing for both the conference and national post-season tournaments. This was done to allow for study replication since teams will continue playing different lengths into the post-season. However, this difference may have caused there to still be acute effects of pitching, such as joint inflammation, to be present in the throwing elbows of the participants in our study. The presence of inflammation during imaging sessions would possibly limit medial elbow, and thus UCL, laxity measurements. Additionally, the discrepancies between the current research and that by Keller et al. in the differences from pre- to post-season U-H gap may also be artifact as the differences were less than 0.5 mm. The decreases in the U-H gap of our participants from pre- to post-season, while non-significant, was not expected. It was expected that as the total throwing load of the season increased, an increase in medial elbow laxity and thus an increase in U-H gap would be seen. This expectation was based on the increased U-H gap seen in baseball pitchers throwing arms compared to their non-throwing arms in several of the research studies previously mentioned. While the present research did not attempt to evaluate this possibility, one potential reason for a decrease in U-H gap from pre- to post-season in the stressed conditions would be osteophyte development on the lateral side of the elbow. The pitching motion is a highly dynamic motion and osteophyte formation in the UCL is often documented. Formation of similar osteocytes on the lateral side of the elbow would potentially prevent full frontal plane movement and thus limit U-H gap in stressed conditions, and may explain the gradual decrease in U-H gap, as opposed to a sudden change.

Bilateral Differences in UCL Properties:

The structural properties of the UCL in the non-throwing arm and the bilateral differences seen in the pre-season imaging session can be compared to UCL structural property values in the non-throwing arms of baseball pitchers and bilateral differences in the literature. Bilateral differences in the measurements taken for each structural property of the UCL during pre-season imaging in the present study can be seen in Figure 14. Only the pre-season imaging results are compared to previous literature in the following paragraphs as there is a void in the literature regarding longitudinal bilateral imaging of the UCL. Additionally, much of the imaging in the literature was conducted while participants were either in an off-season or pre-season training period and not mid- or post-season, justifying the use of the pre-season measurements from our research to the property measurements reported for the non-throwing arm in previous studies[6,12,56]. Our research did demonstrate some significant changes in UCL structural properties from pre- to post-season in both the throwing and non-throwing arms of the participants as seen in Table 3 such as with UCL length and UCL thickness (*Figure 15*).

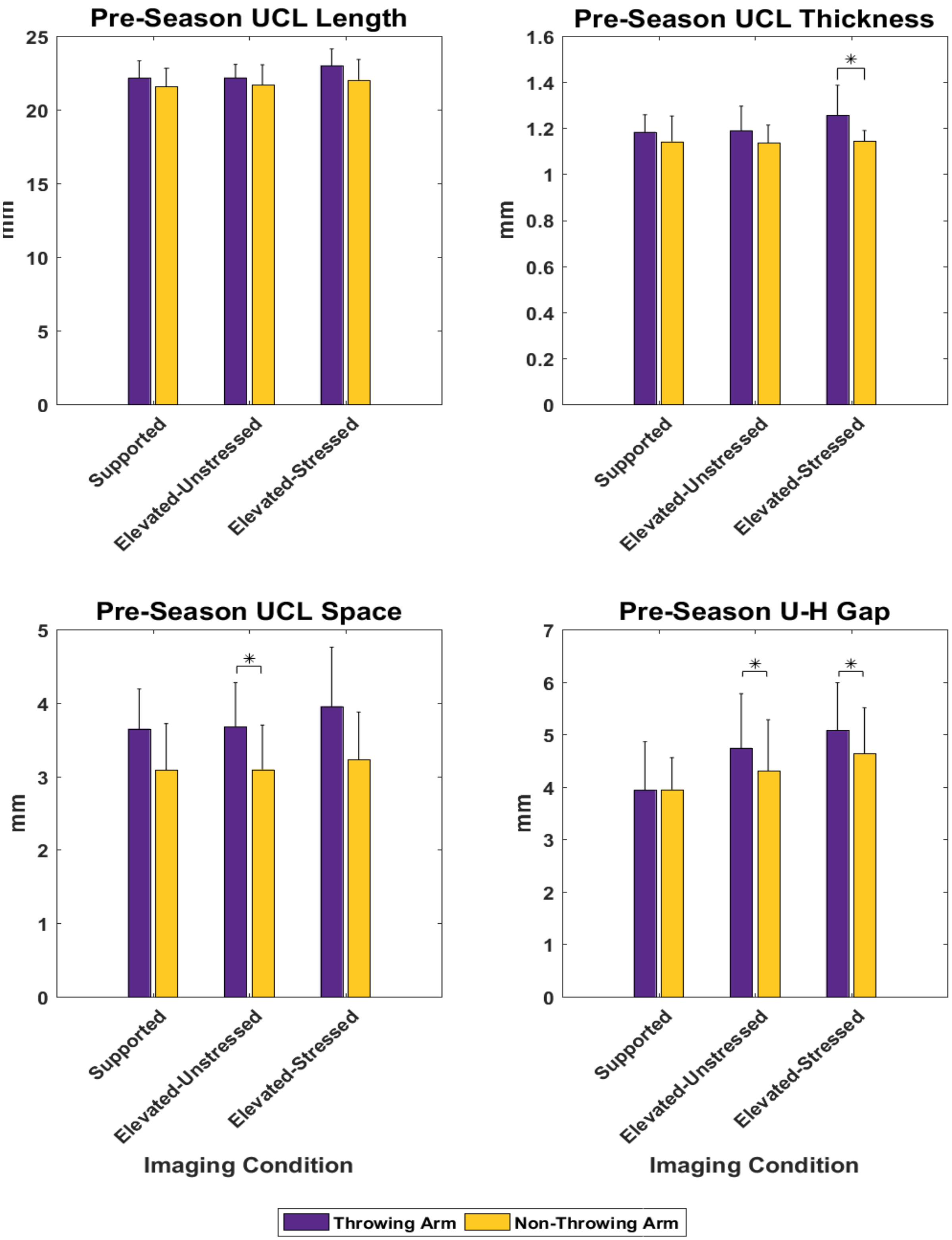


Figure 14. ***Pre-Season Bilateral differences in UCL Structural Properties.*** **p <0.05*
Pre-season measurements for UCL length, thickness, and space, and U-H gap in each of the three imaging conditions.

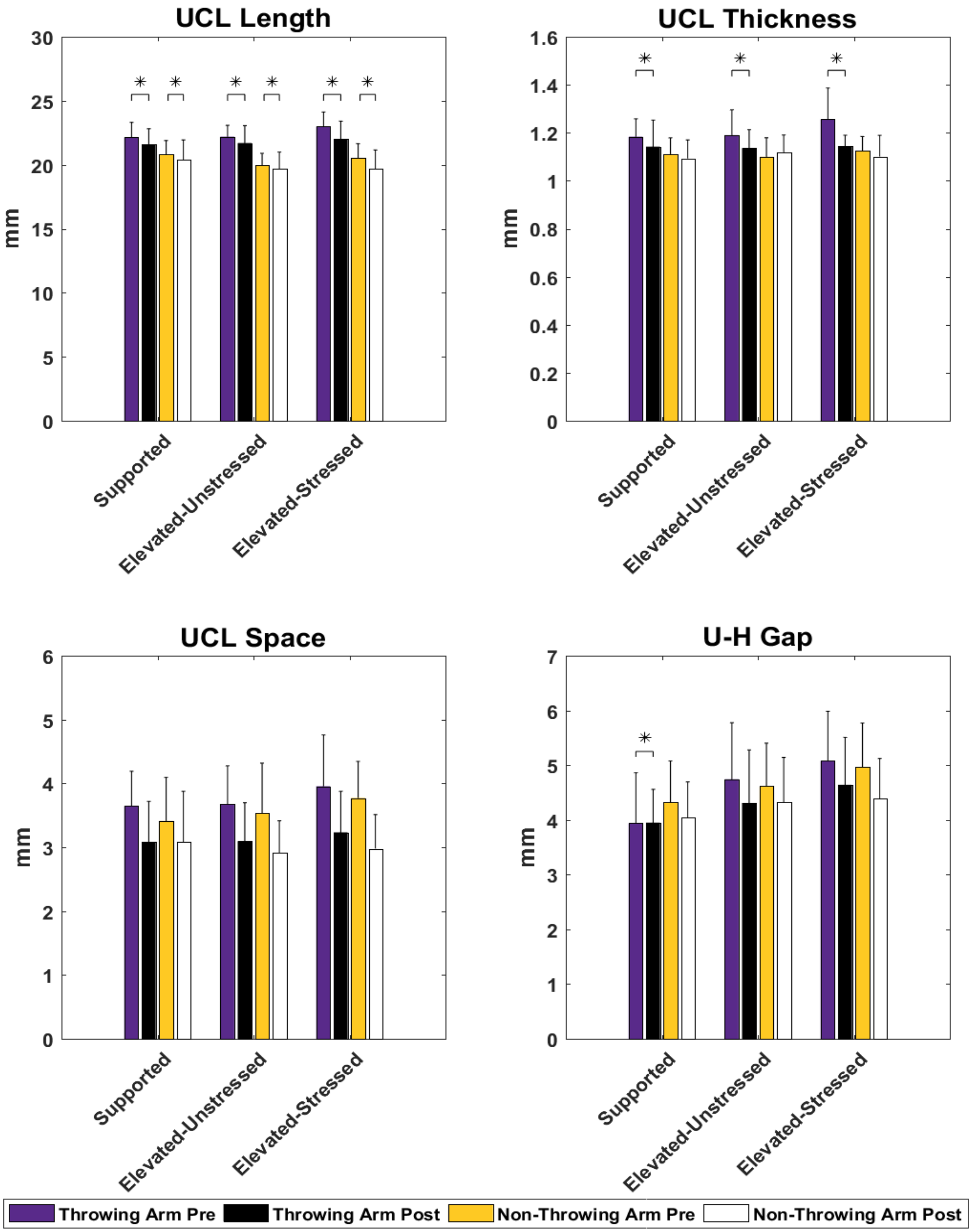


Figure 15. ***Pre- and Post-Season UCL Structural Property Measurements.*** **p <0.05*
Bilateral pre- and post-season measurements for UCL length, thickness, and space, and U-H gap in each of the three imaging conditions.

Similar to our results for the length the UCL in the throwing arm, our results for the non-throwing arm were shorter than those previously by Bica et al. (2015) (Gravity-stressed: 24.7 ± 1.4 mm vs 21.69 ± 1.36, Valgus-stressed: 25.0 ± 1.9 mm vs 22.02 ± 1.39). The non-throwing arm in our research was 0.50 and 0.99 mm shorter than the throwing arm, compared to being 0.3 mm longer, and 0.9 mm shorter in the gravity- and valgus-stressed conditions. As with the length of the UCL in the throwing arm, the differences in absolute UCL length values may be a result of different definitions on the ultrasound images of the ligament's origin and insertion in our research compared to previously the prior study by Bica et al (2015).

The results of the present research for the thickness of the UCL in non-throwing arms of baseball pitchers are smaller than those from Marshall et al. (2015), the only prior bilateral imaging of UCL thickness (1.89 ± 0.59 mm vs 1.14 ± 0.05 mm) in a valgus-stressed condition. The non-throwing arm measurement reported by Marshall was not significantly different than the throwing arm of the sample (p = 0.82). The results of our research did not confirm these results, as the non-throwing arms of the imaged in the current research demonstrated a significantly smaller UCL thickness than that of the throwing arms (p = 0.038). Additional years of playing baseball (8.3 years[52] vs 11.4 years), and specifically pitching experience, may have contributed to the increased bilateral difference in UCL thickness seen in our sample.

During the pre-season imaging session, UCL space in the non-throwing arms of participants in the present research measured 3.09 ± 0.63, 3.10 ± 0.60, and 3.23 ± 0.64 mm in the Supported, Elevated-Unstressed, and Elevated-Stressed conditions, respectively. The increases seen in UCL space measurement from the Supported condition to Elevated-Unstressed condition, and then again from the Elevated-Unstressed to the Elevated-Stressed condition are reasonable. Considering the anatomy of the medial elbow, it is understandable that the UCL space measurement would increase from a resting condition with the application of a gravity load (Elevated-Unstressed), and then again with the application of a valgus load (Elevated-Stressed), due to the way in which the measurements were taken in our research, and the way in which the UCL is oriented across the medial aspects of the elbow joint. UCL length was measured as a non-linear trace of the ligament from origin to insertion, and UCL space was measured as the distance from the mid-point of the ligament to the surface of the Humerus in the distal trough of the medial epicondyle. Applying a gravity, and then valgus load, to the elbow would result in the ligament becoming tauter, straightening out from origin to insertion, and, because of the anatomy of the medial elbow, moving superficially in relation to the humeral trough. This movement would ultimately result in an increase in UCL space measurement with the application of each load.

These values from our research for UCL space in the non-throwing arms of baseball pitchers are smaller than those of previous studies. A large sample of stressed ultrasound images of the UCL in professional baseball pitchers reported a mean value for UCL space in the non-throwing arm of 4.82 ± 1.32 mm in a supported condition[12,56]. The study by Nazarian et al. (2003) reported non-throwing arm UCL space values of 5.3 ± 1.0 mm and 4.8 ± 0.9 mm in a supported condition and a valgus-loaded condition, respectively. Imaging performed on a sample of 22 high school pitchers reported mean UCL space measurement of 6.71 ± 1.05 mm[52]. The bilateral differences in UCL space of 0.56 mm, 0.57 mm, and 0.72 mm for the Supported, Elevated-Unstressed, and Elevated-Stressed conditions seen in our research are also much smaller than those reported in previous literature, which tended to range between 1.0 and 1.3 mm, with the exception of those reported by Marshall et al. (2015). Similar to the values for UCL space, the differences in bilateral symmetry for UCL space between the present research and values previously reported may be a result of differences in how the measurements were taken. The bilateral asymmetry seen both in the present research as well as the previous literature fell between 15-18% of the UCL space measurement for the throwing arm in each condition, again with the exception of the study by Marshall on a sample of high school pitchers.

Pre-season U-H gap mean values for the non-throwing arm in our sample of pitchers are slightly larger than most of the values previously reported for U-H gap in baseball pitchers' non-throwing arms, however they are comparable to those from a study specifically focused on collegiate baseball pitchers. A cross-sectional imaging of pitchers at the collegiate level during the off-season reported a mean of 4.3 ± 0.9 mm compared to our mean U-H gap of 4.31 ± 0.97 mm in a gravity-stressed condition, and 4.9 ± 0.8 mm compared to our result of 4.64 ± 0.87 mm in valgus-loaded condition[6]. The values reported from our pre-season imaging vary from Bica et al. just 0.2% and 5.3% in the gravity-stressed and valgus-loaded conditions. Literature values for U-H gap in the non-throwing arm of samples other than collegiate level pitchers were slightly smaller in both a supported (2.94 ± 0.12 mm[12,56], 2.5 ± 0.7 mm[56], and 3.58 ± 0.60 mm[22] vs 3.95 ± 0.61 mm) and in a valgus-stressed condition (3.72 ± 0.92 mm[12,56], 3.0 ± 1.0 mm[56], and 4.46 ± 0.86 mm[22] vs 4.64 ± 0.87 mm). In research not performed on collegiate pitchers, U-H gap measurements in the non-throwing arm are slightly smaller than those seen in our research. A large study of professional baseball pitchers reported U-H gap measurements of 2.94 ± 0.12 mm and 3.72 ± 0.92 mm in supported and stressed conditions and a second, similar study reported measurements of 2.5 ± 0.7 mm and 3.0 ± 1.0 mm in supported and stressed conditions[12,56]. In a sample of 40 professional pitchers, Ellenbecker et al. (1998) report non-throwing arm U-H gap means of 3.58 ± 0.60 mm and 4.46 ± 0.86 mm in a supported condition and with the application of 150N of valgus stress using radiographic imaging.

The variation seen in U-H gap values between previously reported research as well as with our own research indicates that this measurement may be the structural property that is most influenced by individual anatomical differences and adaptations to throwing. As previous authors have noted, U-H gap will undergo the most dramatic change with the presence of a significant injury to the UCL[11]. The link between changes in this property and an injury believed to result from chronic microtraumas from overhead throwing support the concept that as the amount of pitching performed by an individual varies, and as the amount that each individual uniquely adapts to the stress of pitching, the U-H gap measurement would vary within a sample and the population as well. This concept strongly suggests the need for new imaging techniques or evaluation modalities to track the health of the UCL in asymptomatic pitchers in order to detect elevated injury risk prior to the occurrence of a significant injury to the UCL.

Biweekly Changes in UCL Structural Properties: Overall, the measurements recorded in this study did not show any significant variations in UCL length, thickness, or space, or in the U-H gap between the bi-weekly in-season imaging sessions. With the exception of UCL thickness in the Supported (ICC = .210) and Elevated-Unstressed (ICC = .222), the experimenter that was responsible for collecting all images used to measure structural properties of the UCL demonstrated excellent day-to-day reliability (ICC range = .753-.944). These reliability values are in agreement with previous research that demonstrated excellent reliability for the use of sonographic imaging to measure UCL length and U-H gap compared to MRI[6]. The low ICC value for the thickness measurements, especially in the Supported and Elevated-Unstressed conditions may be a result of the small sample size of the reliability study (n=10), and a low between mean square (BMS) value for UCL thickness measurements. Low BMS may drive down ICC values while the SEM remains reasonable. The SEM for UCL thickness in our research was 12-13% of the UCL thickness mean value. The overall good-to-excellent reliability demonstrated by the experimenter in this research supports the validity of comparing measurements between biweekly imaging sessions.

While there were not any significant trends in any of the four structural properties throughout the season, there was a noticeable increase in U-H gap in the Supported condition towards the beginning of the season and also a noticeable decrease in UCL length from the pre-season imaging session to the first in-season imaging session in all three imaging conditions. It should be noted that both of these measurements seem to stabilize after these changes take place early in the season.

The increase in U-H gap may have been a result of adjustments in the position of the participant in the arm position splint such as an elevation of the splint compared to the height of the treatment table. This change would place the upper arm at an angle that may lead to increased U-H gap compared to the splint being slightly below the height of the table. Another potential explanation for this difference seen in U-H gap would be a change in the glenohumeral joint positioning, similar to a change in splint position compared to the treatment table, or possibly an increase in anterior shoulder joint laxity as a result of the introduction of heavy throwing bouts in the time of the first two in-season imaging sessions compared to the pre-season imaging. Either one of those potential changes may change the angle of the humerus compared to being parallel to the splint. A decrease in this angle compared to pre-season imaging would result in an increase in U-H gap as the distal end of the humerus would move slightly away from the ulnar head. The decrease in UCL length in the first in-season imaging session compared to the pre-season imaging session can potentially be attributed to the introduction of heavy throwing bouts compared to the off-season nature of the pre-season imaging. The introduction of frequent and heavy throwing bouts may have led to inflammation in the joint capsule compressing the UCL. The stability of the decreased UCL length measurement throughout the remainder of the season may also be directly linked to the decrease seen in U-H gap from pre- to post-season.

Two potential explanations for the lack of significant changes in these properties are the health and the age/experience of the participants included in this sample. The stability seen in the UCL properties may be a result of the throwing arm elbows of the nine players included in the results remaining healthy throughout the season. Changes in the UCL structural properties would be expected, as were seen in this study, towards the very beginning of the season as pitchers are introducing and the increasing their throwing load. However, once that throwing load reaches its steady state for the season, it is not surprising that pitchers would not demonstrate any sort of ongoing changes in said properties as long as those pitchers remain healthy.

The relative consistency of the structural properties may also be due to the age and playing experience of the participants included in this sample. The participants had 8.44 ± 2.79 years of pitching experience prior to the season in which the research was conducted. There is a possibility that the UCL in elite Division I baseball pitchers has already undergone healthy adaptations to counter the increased load of the overhead pitching motion and thus was not exposed to a novel stimulus that would have induced changes in the structural properties of the ligament. Evidence supporting the existence of previous adaptations in the structural properties of the UCL prior to the baseball season during which this study was performed can be seen in the main effects displayed in Figure 10. Additional, post-hoc, t-tests were performed to examine effects for arm during only the pre-season imaging session, as several of the structural properties displayed near-significant interaction effects (*Figure 14).* The significant differences U-H gap between the participants' throwing and non-throwing arms in the Elevated-Unstressed (4.74 mm vs 4.31 mm) and Elevated-Stressed (5.08 mm vs 4.64 mm) conditions supports this assertion. Ciccotti, Ciccotti, and Nazarian describe the U-H gap as the structural property that provides the most insight into the presence of a significant injury to the UCL[11]. Citing their numerous in vivo as well as cadaveric studies of the UCL, they suggest that an increase of 2 or more mm in U-H gap with the application of valgus load, *and* a bilateral asymmetry of 1 or more mm in the increase with loading may be indicative of UCL injury. Understanding that UCL injuries are often the result of chronic stresses from overhead throwing, and that U-H gap is the structural property most closely linked to UCL injury, it is then reasonable to state that the bilateral difference seen in U-H gap prior to the season is evidence of the UCL having undergone adaptations in response the previous years of overhead throwing.

The significant differences seen from pre- to post-season imaging sessions without trends in significant biweekly differences may be a result of the pitching status of the participants at the time of imaging, as well as possibly a result of increased proficiency of the researcher. Participants were performing routine high load pitching bouts at the time of the post-season imaging session, as it was scheduled at the conclusion of the regular season, yet the team was preparing for post-season tournament play. This is a different status than the pre-season imaging session, when participants were in an off-season period and not routinely performing high loads of pitching. It is not yet known if recent throwing loads have an acute impact on structural property measurements compared to a period without recent throwing bouts. The theory that throwing load may impact the structural properties of the UCL may be supported as the few noticeable changes in structural properties in UCL length and U-H gap took place near the beginning of the in-season measurements, when heavy pitching bouts were being introduced, and then seemed to stabilize for the remainder of the season.

Another potential explanation for the significant differences between pre- and post-season measurements is changes in the participant and researchers experience and comfort level with each other and the imaging protocol. Participants may have become more accustomed to the arm-position splint, and trusted the research protocol more by the post-season imaging session, and thus may have relaxed their throwing arm more during the post-season session. The researcher may have become more proficient at recording precise images of each individual, accounting for their anatomical variations, after 11 imaging sessions of the throwing arm. This may have led to the significant differences in the pre- to post- season measurements of the structural properties during data analysis, compared to the data from the biweekly imaging sessions.

Relationships between Pitching Workload and Changes in UCL Properties: Low to moderate correlations were found between pitching workload variables and changes in the structural properties of the UCL. It is widely accepted that the majority of soft tissue pitching injuries including those to the UCL, and especially those injuries in younger athletes, are a result of the cumulative workload due to pitching[28,61]. One of the reasons that this study may not have demonstrated stronger correlations between pitching workload and changes in UCL properties is that the pitchers were asked to self-report their pitching workloads. Future research should seek to work with team coaching/training staff to attain access to objective pitching workload data. There are few studies that have attempted to correlate changes in UCL structural property prior to injury with a pitcher’s workload at the time. Keller et al. (2015) studied high school pitchers and found an increase in the thickness of the UCL from pre- to post-season in the throwing arm of the UCL.

They also found that increase was significantly associated with the number of bullpen sessions thrown per week. Looking at slightly older athletes that may be more representative of elite collegiate pitchers, one study attempted to correlate several different workload metrics to injury risk in Major League baseball players, but did not find a single workload metric that was significantly correlated[42]. Again, it should be recognized that this study was examining injury, and not changes in the properties in asymptomatic pitchers. The results of our research continue to demonstrate the need for the development of a new screening modality or protocol able to detect the acute effects of pitching on the UCL that lead to the chronic changes that have been documented the literature and supported by our research, that are believed to lead to significant injuries to the UCL. Such a modality would be of tremendous use to both coaches and medical personnel working with baseball pitchers to maintain their health throughout a training period, competitive season, and entire careers.

Relationships between Perceived Elbow Stiffness and Changes in UCL Properties: The self-reported perceived stiffness values displayed low to moderate correlations with the changes in the structural properties of the UCL. As the structural properties of the UCL remained rather stable between in-season imaging sessions, and none of the participants experienced elbow injuries during this study, it is conceivable that participants would not have noticed any changes in the perception of elbow stiffness, however questionnaire data was not evaluated from pre- to post season. Additionally, the absence of strong relationships between these self-reported values and the properties of the elbow could potentially be attributed to the inconsistency of when the self-reported questionnaires were administered, at each imaging session, in relationship to their most recent heavy pitching bout. Inflammation in the elbow can be typical after a heavy bout of pitching, which might lead to changes in perceived elbow stiffness, however we did not control how soon after a pitching bout the imaging sessions were scheduled.

Limitations

The present study had several limitations including: 1) a relatively small sample size, 2) the design of the arm position splint, and 3) the inability to completely control the timing of imaging sessions compared to recent activities.

The sample size of nine healthy NCAA Division I baseball pitchers who completed the research and were included in the results may have been a limiting factor when considering the results of the present study. The sample of 12 healthy pitchers that initially enrolled in the study would be typical of the number of healthy pitchers found on a NCAA Division I baseball team. Teams will commonly list 15-17 pitchers on their active roster, and it can be expected that 25-30% of them would not meet the inclusion criteria of not having previous elbow surgery[27]. The remaining pitchers would match the initial sample size used in this study.

A second limitation of the current study is in the design of the custom adjustable-width arm position splint used to maintain participants' arm position during all imaging sessions. In the Elevated-Unstressed and Elevated-Stressed conditions the participant's upper arm was supported by a 4 cm thick foam block. This block was used to allow the forearm to move in the frontal plane due to a valgus torque created either by gravity or through the 1-kg weight placed in the participants' hand. However, as the splint was designed to be used bilaterally there was still material under the forearm that would come into contact with, and support, the forearm if there was more than 14° of frontal plane movement at the elbow. Participants' forearms were limited to

14° of movement, thus limiting the amount that the U-H gap could open, and thus it is conceivable that there may have been a bit of a ceiling effect. In addition to affecting the measurements of the U-H gap, limiting the frontal plane movement of the forearm at the elbow may also have contributed to the smaller UCL space measurements reported in our research compared to prior literature. Limiting the extent to which the U-H joint was able to expand may have limited how taut the UCL became in the gravity- and valgus-loaded conditions, limiting the maximum value of UCL space for an individual. In the future, the use of left- and right-arm specific arm splints that do not have this support to allow for unrestricted movement in the frontal plane would prevent this limitation.

The final limitation in this research was the researchers' incapability to control the timing of imaging sessions compared to participants' immediately previous throwing or upper body resistance training session. Throwing or upper body resistance training sessions immediately prior to an imaging session may have resulted in inflammation in the elbow joint during imaging. An increase in inflammation in the joint may compress the UCL or prevent complete opening of the U-H gap. The effect of increased inflammation may have caused skewed results when examining session to session changes in the structural properties of the UCL if the timing of the imaging session compared to the immediately previous throwing or resistance training session was not consistent across the season.

Future Directions

There are several directions that can be explored by research continuing on the findings of the present research. Replicating our longitudinal research design, with the addition of recruiting pitchers from multiple teams, would possibly allow for the larger sample size needed to reach significance and results that may be more transferable to the broader population of collegiate baseball pitchers. Additionally, including participants from different teams in the research sample may increase the likelihood of an injury occurrence in the sample as it could be expected that each organization would have variations in their training and injury prevention protocols, based on each coach and athletic trainer's individual beliefs and practices about each factor. Some variables that would be expected to differ between teams would include resistance training program, load and frequency, bullpen session length and frequency, scrimmage and in-game pitch count and appearance frequency, as well as the total pitching load over the course of the season. It could also be expected when recruiting pitchers from different levels of collegiate baseball, that a pitcher's access to baseball-specific medical attention would vary (i.e. Division I vs Junior College), and thus the amount of preventative treatment that an individual undergoes would vary as well. If multiple teams were incorporated into the research sample during the same collegiate baseball season, the effect of specific, team-wide training or recovery protocols on the properties of the UCL could be systematically evaluated. Matching participants across protocols based on throwing load, the research could determine if a particular recovery methodology between throwing bouts, or training regimen across the entirety of the season has an effect on the properties of the UCL. Coaching staffs, medical personnel, and players would all support determining which protocols will best be able to protect the UCL over the length of a pitcher's career.

One significant development in follow-up research to this project would be standardization of time since last throwing bout when scheduling data collection sessions. This would help to decrease the impact of inflammatory response by standardizing it across the sample. Although it can be assumed that individual pitchers will still vary in the amount of inflammatory response present in their elbow due to several factors including age, throwing experience, fatigue, and the amount of throwing performed in the bout.

To attempt to understand more of the acute effects of pitching within a single season, future research should attempt to measure and track the material properties, in addition to the structural properties described in this research, of the UCL in baseball pitchers throughout the course of the season. Tracking both the structural and material properties of the ligament would provide novel insight into any potential material changes in the UCL, while also tracking the same structural properties in an effort to confirm the findings of this research that there were not any significant changes in structural properties of the UCL between biweekly collections in healthy pitchers. Using a technique such as shearwave ultrasound elastography to examine the material stiffness of the UCL, may be a valuable tool in detecting changes in the ligament going forward. If structural properties remain constant, and there is a change in material stiffness, then it can be assumed that there has been a change in the modulus of the ligament. Previous research in muscle has shown significant changes in the modulus of a soft-tissue structure immediately prior to an injury[65]. Additionally, as noted by Karakolis, there is a need for an integrated approach to injury prevention in baseball pitchers, and it has yet to be seen if perhaps changes in the modulus of the UCL may be correlated with any of the workload metrics examined in previous research.

Preliminary research in our lab using shearwave ultrasound elastography to measure the material properties of the UCL have demonstrated the ability to successfully measure the modulus of the ligament in both non-overhead throwers (healthy college participants), as well as in collegiate baseball pitchers. Additionally, our preliminary data suggests that the stress placed on the medial elbow, and specifically the UCL, as a result of pitching does result in changes in the material properties of the UCL. The data from this preliminary work shows that the UCL of the throwing arm in healthy collegiate baseball pitchers is significantly less stiff than the UCL of the non-throwing arm at both 50% (175.02 ± 31.05 vs 218.01 ± 3.06 kPa) and 70% (197.15 ± 35.70 vs 260.15 ± 46.39 kPa) of the length of the ligament (*Figure 16*). This data was collected while the participants were in an off-season period and not regularly performing bouts of pitching. Future research should attempt to evaluate if there is variation in the material properties of the UCL throughout a season, and if there is a relationship between the stiffness of the UCL and an individual's injury risk.

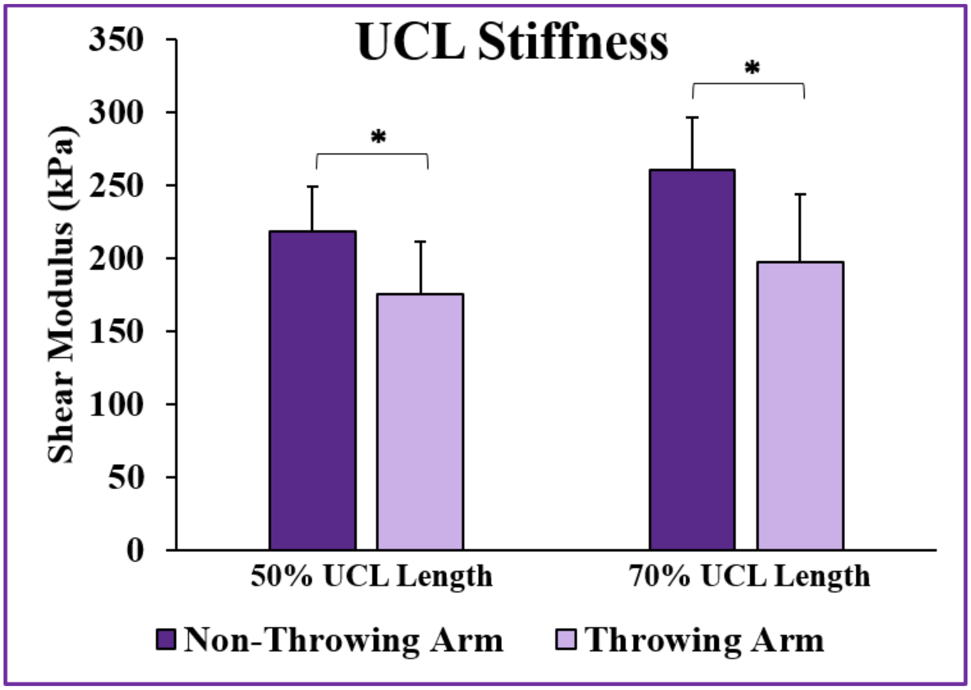


Figure 16. ***Pre-Season Bilateral differences in UCL Stiffness.*** **p <0.05*
Pre-season measurements for UCL stiffness at 50% and 70% of the length of the UCL in collegiate baseball pitchers.

Conclusions

In conclusion, the structural properties of the UCL in a sample of collegiate baseball pitchers demonstrated significant changes from pre- to post-season for UCL length and thickness in all three imaging conditions and for U-H gap in the Supported condition in the throwing arm. There were fewer main effects for time and no significant interaction effects for any outcome variable across a single collegiate season. However, our research did not show significant variation for any of the structural properties of the UCL throughout the course of a single baseball season based on biweekly data collections. Additionally, none of the workload metrics or perceived elbow stiffness variables strongly correlated with the changes in the structural properties of the UCL. These results suggest the need for a different modality to measure changes in the UCL prior to injury, such as ultrasound elastography.

REFERENCES CITED

1. Aubry S, Risson J, Kastler A, et al. Biomechanical properties of the calcaneal tendon in vivo assessed by transient shear wave elastography. *Skeletal Radiol*. 2013;42(8):1143-1150.

2. Azar FM, Andrews JR, Wilk KE, Groh D. Operative treatment of ulnar collateral ligament injuries of the elbow in athletes. *Am J Sports Med*. 2000;28(1):16-23.

3. Azizi G, Keller JM, Mayo ML, et al. Shear wave elastography and cervical lymph nodes: Predicting malignancy. *Ultrasound Med Biol*. 2016;42(6):1273-1281.

4. Bercoff J, Pernot M, Tanter M, Fink M. Monitoring thermally-induced lesions with supersonic shear imaging. *Ultrason Imaging*. 2004;26(2):71-84.

5. Bernas GA, Ruberte Thiele RA, Kinnaman KA, Hughes RE, Miller BS, Carpenter JE. Defining safe rehabilitation for ulnar collateral ligament reconstruction of the elbow: A biomechanical study. *Am J Sports Med*. 2009;37(12):2392-2400.

6. Bica D, Armen J, Kulas AS, Youngs K, Womack Z. Reliability and precision of stress sonography of the ulnar collateral ligament. *Journal of Ultrasound in Medicine*. 2015;34(3):371-376.

7. Cage DJN, Abrams RA, Callahan JJ, Botte MJ. Soft tissue attachments of the ulnar coronoid process: An anatomic study with radiographic correlation. *Clin Orthop*. 1995;320:154-158.

8. Cain Jr EL, Andrews JR, Dugas JR, et al. Outcome of ulnar collateral ligament reconstruction of the elbow in 1281 athletes: Results in 743 athletes with minimum 2-year follow-up. *Am J Sports Med*. 2010;38(12):2426-2434.

9. Callaway GH, Field LD, Deng X, et al. Biomechanical evaluation of the medial collateral ligament of the elbow. *J Bone Joint Surg Am*. 1997;79(8):1223-1231.

10. Chen FS, Rokito AS, Jobe FW. Medial elbow problems in the overhead-throwing athlete. *J Am Acad Orthop Surg*. 2001;9(2):99-113.

11. Ciccotti MC, Nazarian LN, Ciccotti MG. Ultrasound imaging of ulnar collateral ligament injury. In: Dines JS, Altchek DW, eds. *Elbow ulnar collateral ligament injury: A guide to diagnosis and treatment.* Boston: Springer; 2015:79-91.

12. Ciccotti MG, Atanda A, Nazarian LN, Dodson CC, Holmes L, Cohen SB. Stress sonography of the ulnar collateral ligament of the elbow in professional baseball pitchers. *Am J Sports Med*. 2014;42(3):544-551. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4131844/. Accessed Apr 21, 2017. doi: 10.1177/0363546513516592.

13. Conte SA, Fleisig GS, Dines JS, et al. Prevalence of ulnar collateral ligament surgery in professional baseball players. *The American Journal of Sports Medicine*. 2015;43(7):1764-1769. http://journals.sagepub.com/doi/full/10.1177/0363546515580792. doi: 10.1177/0363546515580792.

14. Conway JE, Jobe FW, Glousman RE, Pink M. Medial instability of the elbow in throwing athletes. treatment by repair or reconstruction of the ulnar collateral ligament. *J Bone Joint Surg Am*. 1992;74(1):67-83.

15. De Maeseneer M, Brigido MK, Antic M, et al. Ultrasound of the elbow with emphasis on detailed assessment of ligaments, tendons, and nerves. *Eur J Radiol*. 2015;84(4):671-681.

16. De Smet AA, Winter TC, Best TM, Bernhardt DT. Dynamic sonography with valgus stress to assess elbow ulnar collateral ligament injury in baseball pitchers. *Skeletal Radiol*. 2002;31(11):671-676.

17. DiGiovine NM, Jobe FW, Pink M, Perry J. An electromyographic analysis of the upper extremity in pitching. *Journal of shoulder and elbow surgery*. 1992;1(1):15-25.

18. Dillman CJ, Smutz P, Werner S. Valgus extension overload in baseball pitching. *Med Sci Sports Exerc*. 1991;23(suppl 4):S135.

19. Drakonaki EE, Allen GM, Wilson DJ. Ultrasound elastography for musculoskeletal applications. *Br J Radiol*. 2014.

20. Dugas JR, Walters BL, Beason DP, Fleisig GS, Chronister JE. Biomechanical comparison of ulnar collateral ligament repair with internal bracing versus modified jobe reconstruction. *Am J Sports Med*. 2016;44(3):735-741.

21. Eby SF, Song P, Chen S, Chen Q, Greenleaf JF, An K. Validation of shear wave elastography in skeletal muscle. *J Biomech*. 2013;46(14):2381-2387.

22. Ellenbecker TS, Mattalino AJ, Elam EA, Caplinger RA. Medial elbow joint laxity in professional baseball pitchers a bilateral comparison using stress radiography. *Am J Sports Med*. 1998;26(3):420-424.

23. Erickson BJ, Gupta AK, Harris JD, et al. Rate of return to pitching and performance after tommy john surgery in major league baseball pitchers. *Am J Sports Med*. 2014;42(3):536-543.

24. Evans A, Whelehan P, Thomson K, et al. Differentiating benign from malignant solid breast masses: Value of shear wave elastography according to lesion stiffness combined with greyscale ultrasound according to BI-RADS classification. *Br J Cancer*. 2012;107(2):224-229.

25. Evans A, Sim YT, Thomson K, Jordan L, Purdie C, Vinnicombe SJ. Shear wave elastography of breast cancer: Sensitivity according to histological type in a large cohort. *The Breast*. 2016;26:115-118.

26. Ferraioli G, Lissandrin R, Tinelli C, et al. Liver stiffness assessed by transient elastography in patients with β thalassaemia major. *Annals of hepatology*. 2016;15(3):410-417.

27. Fleisig GS. Analytics of the tommy john pitching epidemic. *Sloan Sports Medicine Conference*. Mar 12 2015.

28. Fleisig GS, Andrews JR, Cutter GR, et al. Risk of serious injury for young baseball pitchers: A 10-year prospective study. *The American Journal of Sports Medicine*. 2011;39(2):253-257. http://journals.sagepub.com/doi/abs/10.1177/0363546510384224. Accessed Apr 24, 2017. doi: 10.1177/0363546510384224.

29. Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanisms. *Am J Sports Med*. 1995;23(2):233-239.

30. Fleisig GS, Barrentine SW, Zheng N, Escamilla RF, Andrews JR. Kinematic and kinetic comparison of baseball pitching among various levels of development. *Journal of Biomechanics*. 1999;32(12):1371-1375. http://www.sciencedirect.com/science/article/pii/S002192909900127X. Accessed Apr 24, 2017. doi: 10.1016/S0021-9290(99)00127-X.

31. Fortenbaugh D, Fleisig GS, Andrews JR. Baseball pitching biomechanics in relation to injury risk and performance. *Sports health*. 2009;1(4):314-320.

32. Freehill MT, Safran MR. Diagnosis and management of ulnar collateral ligament injuries in throwers. *Current sports medicine reports*. 2011;10(5):271-278.

33. Gao Q, Shao D, Pan A, Gao M, Liu Z, Liang C. Noninvasive assessment of liver stiffness by transient elastography (FibroScan) in liver fluke disease. *Eur J Gastroenterol Hepatol*. 2016;28(1):70-73.

34. Gutierrez NM, Granville C, Kaplan L, Baraga M, Jose J. Elbow MRI findings do not correlate with future placement on the disabled list in asymptomatic professional baseball pitchers. *Sports Health: A Multidisciplinary Approach*. 2017;9(3):222-229. http://journals.sagepub.com/doi/full/10.1177/1941738117701769. doi: 10.1177/1941738117701769.

35. Hackel J, Tabacco J. Diagnostic ultrasound of the elbow. *Applied Radiology*. 2014.

36. Hatta T, Giambini H, Uehara K, et al. Quantitative assessment of rotator cuff muscle elasticity: Reliability and feasibility of shear wave elastography. *J Biomech*. 2015;48(14):3853-3858.

37. Hirayama K, Akagi R, Takahashi H. Reliability of ultrasound elastography for the quantification of transversus abdominis elasticity. *Acta radiologica open*. 2015;4(9):2058460115603420.

38. Hurd WJ, Eby S, Kaufman KR, Murthy NS. Magnetic resonance imaging of the throwing elbow in the uninjured, high school–aged baseball pitcher. *Am J Sports Med*. 2011;39(4):722-728.

39. Itoigawa Y, Sperling JW, Steinmann SP, et al. Feasibility assessment of shear wave elastography to rotator cuff muscle. *Clinical anatomy*. 2015;28(2):213-218.

40. Jacobson JA. *Fundamentals of musculoskeletal ultrasound: Expert consult-online.* Elsevier Health Sciences; 2012.

41. Jobe FW, Stark H, Lombardo SJ. Reconstruction of the ulnar collateral ligament in athletes. *J Bone Joint Surg Am*. 1986;68(8):1158-1163.

42. Karakolis T, Bhan S, Crotin R. An inferential and descriptive statistical examination of the relationship between cumulative work metrics and injury in major league baseball pitchers. *Journal of Strength and Conditioning Research*. 2013;27(8):2113-2118. http://www.ncbi.nlm.nih.gov/pubmed/23090322. doi: 10.1519/JSC.0b013e3182785059.

43. Keller RA, Marshall NE, Bey MJ, et al. Pre-and postseason dynamic ultrasound evaluation of the pitching elbow. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*. 2015;31(9):1708-1715.

44. Kijima H, Minagawa H, Tomioka T, et al. Elasticity of the coracoacromial ligament in shoulders with rotator cuff tears: Measurement with ultrasound elastography. *Surgical Science*. 2013;4(09):1.

45. Le Sant G, Ates F, Brasseur J, Nordez A. Elastography study of hamstring behaviors during passive stretching. *PloS one*. 2015;10(9):e0139272.

46. Lee GA, Katz SD, Lazarus MD. Elbow valgus stress radiography in an uninjured population. *Am J Sports Med*. 1998;26(3):425-427.

47. Li Y, Snedeker JG. Elastography: Modality-specific approaches, clinical applications, and research horizons. *Skeletal Radiol*. 2011;40(4):389-397.

48. Loftice J, Fleisig GS, Zheng N, Andrews JR. Biomechanics of the elbow in sports. *Clinics in Sports Medicine*. 2004;23(4):519-530. http://www.sciencedirect.com/science/article/pii/S0278591904000663. Accessed Apr 20, 2017. doi: 10.1016/j.csm.2004.06.003.

49. Lyman S, Fleisig GS, Andrews JR, Osinski ED. Effect of pitch type, pitch count, and pitching mechanics on risk of elbow and shoulder pain in youth baseball pitchers. *Am J Sports Med*. 2002;30(4):463-468.

50. Lyman S, Fleisig GS, Waterbor JW, et al. Longitudinal study of elbow and shoulder pain in youth baseball pitchers. *Med Sci Sports Exerc*. 2001;33(11):1803-1810.

51. Makhni EC, Ahmad CS. Return to pitching after tommy john surgery: Response. *Am J Sports Med*. 2014;42(12):NP55.

52. Marshall NE, Keller RA, Van Holsbeeck M, Moutzouros V. Ulnar collateral ligament and elbow adaptations in high school baseball pitchers. *Sports health*. 2015;7(6):484-488.

53. Miller CD, Savoie III FH. Valgus extension injuries of the elbow in the throwing athlete. *J Am Acad Orthop Surg*. 1994;2(5):261-269.

54. Morrey Bernard F, An K. Articular and ligamentous contributions to. *The American Journal of Sports Medicine*. 1983.

55. Munshi M, Pretterklieber ML, Chung CB, et al. Anterior bundle of ulnar collateral ligament: Evaluation of anatomic relationships by using MR imaging, MR arthrography, and gross anatomic and histologic analysis. *Radiology*. 2004;231(3):797-803.

56. Nazarian LN, McShane JM, Ciccotti MG, O'Kane PL, Harwood MI. Dynamic US of the anterior band of the ulnar collateral ligament of the elbow in asymptomatic major league baseball pitchers 1. *Radiology*. 2003;227(1):149-154.

57. Ophir J, Alam SK, Garra BS, et al. Elastography: Imaging the elastic properties of soft tissues with ultrasound. *Journal of medical ultrasonics*. 2002;29(4):155-171.

58. Ophir J, Cespedes I, Ponnekanti H, Yazdi Y, Li X. Elastography: A quantitative method for imaging the elasticity of biological tissues. *Ultrason Imaging*. 1991;13(2):111-134.

59. Pappas AM. Elbow problems associated with baseball during childhood and adolescence. *Clin Orthop*. 1982;164:30-41.

60. Pappas AM, Zawacki RM, Sullivan TJ. Biomechanics of baseball pitching: A preliminary report. *Am J Sports Med*. 1985;13(4):216-222.

61. Petty DH, Andrews JR, Fleisig GS, Cain EL. Ulnar collateral ligament reconstruction in high school baseball players clinical results and injury risk factors. *Am J Sports Med*. 2004;32(5):1158-1164.

62. Rijke AM, Goitz HT, McCue FC, Andrews JR, Berr SS. Stress radiography of the medial elbow ligaments. *Radiology*. 1994;191(1):213-216. Accessed Apr 21, 2017. doi: 10.1148/radiology.191.1.8134574.

63. Roberts TW. Cinematography in biomechanical investigation: Selected topics in biomechanics. . 1971:41-50.

64. Rosskopf AB, Ehrmann C, Buck FM, Gerber C, Flck M, Pfirrmann CW. Quantitative shear-wave US elastography of the supraspinatus muscle: Reliability of the method and relation to tendon integrity and muscle quality. *Radiology*. 2015;278(2):465-474.

65. Salzano MQ, Bell EA, Hibbert JE, Rider PM, Domire ZJ. Hamstring shear modulus is altered prior to strain injury: A case study. *XXV Congress of the International Society of Biomechanics*. July 12-15 2015.

66. Sandrin L, Fourquet B, Hasquenoph J, et al. Transient elastography: A new noninvasive method for assessment of hepatic fibrosis. *Ultrasound Med Biol*. 2003;29(12):1705-1713.

67. Sasaki J, Takahara M, Ogino T, Kashiwa H, Ishigaki D, Kanauchi Y. Ultrasonographic assessment of the ulnar collateral ligament and medial elbow laxity in college baseball players. *J Bone Joint Surg Am*. 2002;84(4):525-531.

68. Schwab GH, Bennett JB, Woods GW, Tullos HS. The role of the medial collateral ligament. *Clin Orthop*. 1980;146:45-52.

69. Seo J, Yoo J, Ryu J. Sonoelastography findings of biceps tendinitis and tendinosis. *Journal of ultrasound*. 2014;17(4):271-277.

70. Shen ZL, Vince DG, Li Z. In vivo study of transverse carpal ligament stiffness using acoustic radiation force impulse (ARFI) imaging. *PloS one*. 2013;8(7):e68569.

71. Singh H, Osbahr DC, Wickham MQ, Kirkendall DT, Speer KP. Valgus laxity of the ulnar collateral ligament of the elbow in collegiate athletes. *Am J Sports Med*. 2001;29(5):558-561.

72. Siu W, Chan C, Lam C, Lee C, Ying M. Sonographic evaluation of the effect of long-term exercise on achilles tendon stiffness using shear wave elastography. *Journal of science and medicine in sport*. 2016;19(11):883-887.

73. Standring S, Ellis H, Healy J, et al. Gray's anatomy: The anatomical basis of clinical practice. *Am J Neuroradiol*. 2005;26(10):2703.

74. Syversveen T, Midtvedt K, Berstad AE, Brabrand K, Strm EH, Abildgaard A. Tissue elasticity estimated by acoustic radiation force impulse quantification depends on the applied transducer force: An experimental study in kidney transplant patients. *Eur Radiol*. 2012;22(10):2130-2137.

75. Taniguchi K, Shinohara M, Nozaki S, Katayose M. Acute decrease in the stiffness of resting muscle belly due to static stretching. *Scand J Med Sci Sports*. 2015;25(1):32-40.

76. Thavorn K, Coyle D. Transient elastography and controlled attenuation parameter for diagnosing liver fibrosis and steatosis in ontario: An economic analysis. *Ontario health technology assessment series*. 2015;15(19):1.

77. Timmerman LA, Schwartz ML, Andrews JR. Preoperative evaluation of the ulnar collateral ligament by magnetic resonance imaging and computed tomography arthrography evaluation in 25 baseball players with surgical confirmation. *Am J Sports Med*. 1994;22(1):26-32.

78. Tozaki M, Saito M, Joo C, et al. Ultrasonographic tissue quantification of the breast using acoustic radiation force impulse technology: Phantom study and clinical application. *Japanese Journal of Radiology*. 2011;29(8):598-603.

79. Tullos HS, King JW. Throwing mechanism in sports. *Orthop Clin North Am*. 1973;4(3):709.

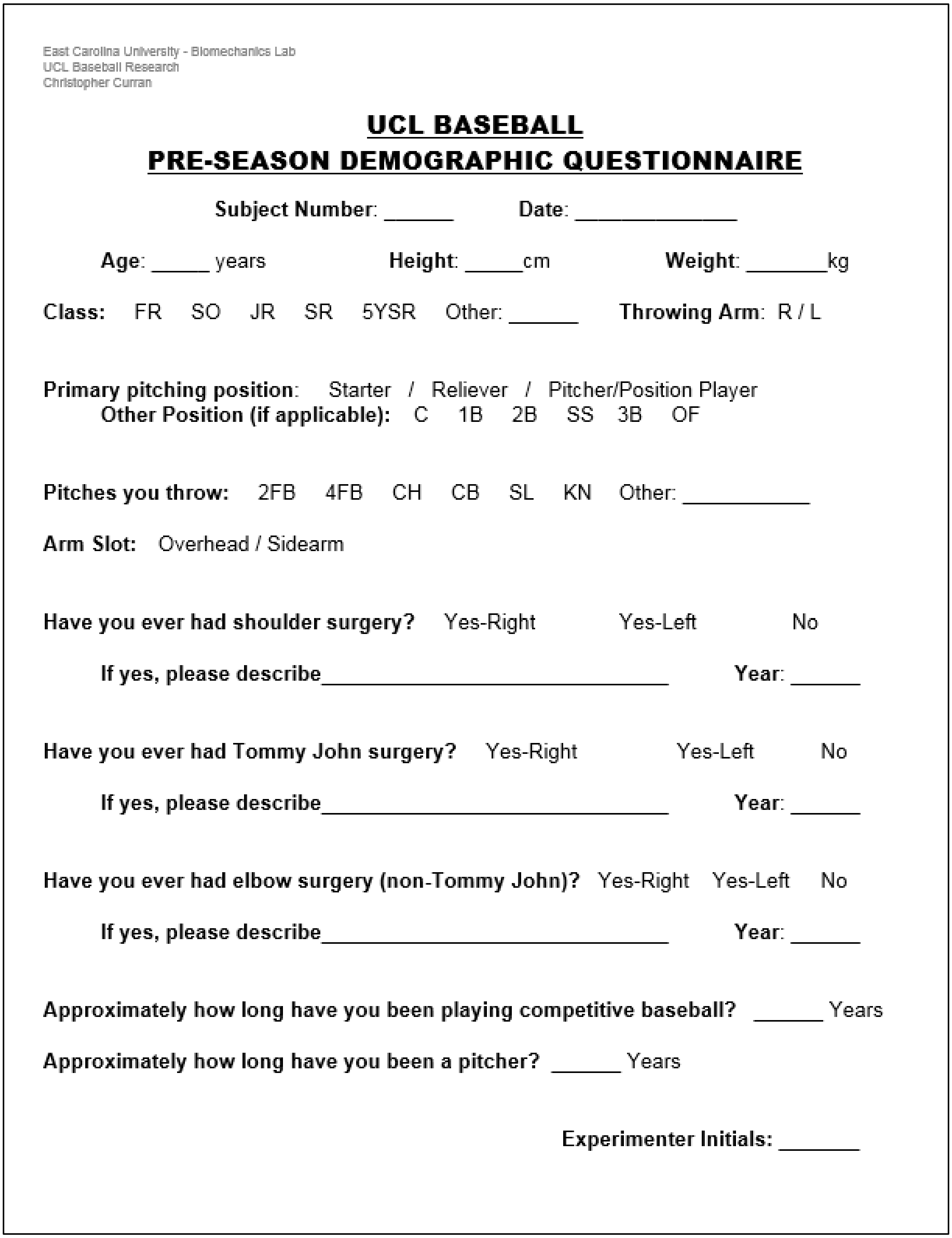
80. Wavreille G, Seraphin J, Chantelot C, Marchandise X, Fontaine C. Ligament fibre recruitment of the elbow joint during gravity-loaded passive motion: An experimental study. *Clin Biomech*. 2008;23(2):193-202.

81. Werner SL, Fleisig GS, Dillman CJ, Andrews JR. Biomechanics of the elbow during baseball pitching. *Journal of Orthopaedic & Sports Physical Therapy*. 1993;17(6):274-278.

82. Wood N, Konin JG, Nofsinger C. Diagnosis of an ulnar collateral ligament tear using musculoskeletal ultrasound in a collegiate baseball pitcher: A case report. *North American Journal of Sports Physical Therapy*. 2010;5(4).

83. Wu C, Chen W, Wang T. Elasticity of the coracohumeral ligament in patients with adhesive capsulitis of the shoulder. *Radiology*. 2015;278(2):458-464.

APPENDIX A: DEMOGRAPHIC QUESTIONNAIRE



East Carolina University - Biomechanics Lab
UCL Baseball Research
Christopher Curran

UCL BASEBALL
PRE-SEASON DEMOGRAPHIC QUESTIONNAIRE

Subject Number: ______ **Date**: ______________

Age: _____ years **Height**: _____cm **Weight**: _______kg

Class: FR SO JR SR 5YSR Other: ______ **Throwing Arm**: R / L

Primary pitching position: Starter / Reliever / Pitcher/Position Player

Other Position (if applicable): C 1B 2B SS 3B OF

Pitches you throw: 2FB 4FB CH CB SL KN Other: ___________

Arm Slot: Overhead / Sidearm

Have you ever had shoulder surgery? Yes-Right Yes-Left No

If yes, please describe______________________________ **Year**: ______

Have you ever had Tommy John surgery? Yes-Right Yes-Left No

If yes, please describe______________________________ **Year**: ______

Have you ever had elbow surgery (non-Tommy John)? Yes-Right Yes-Left No

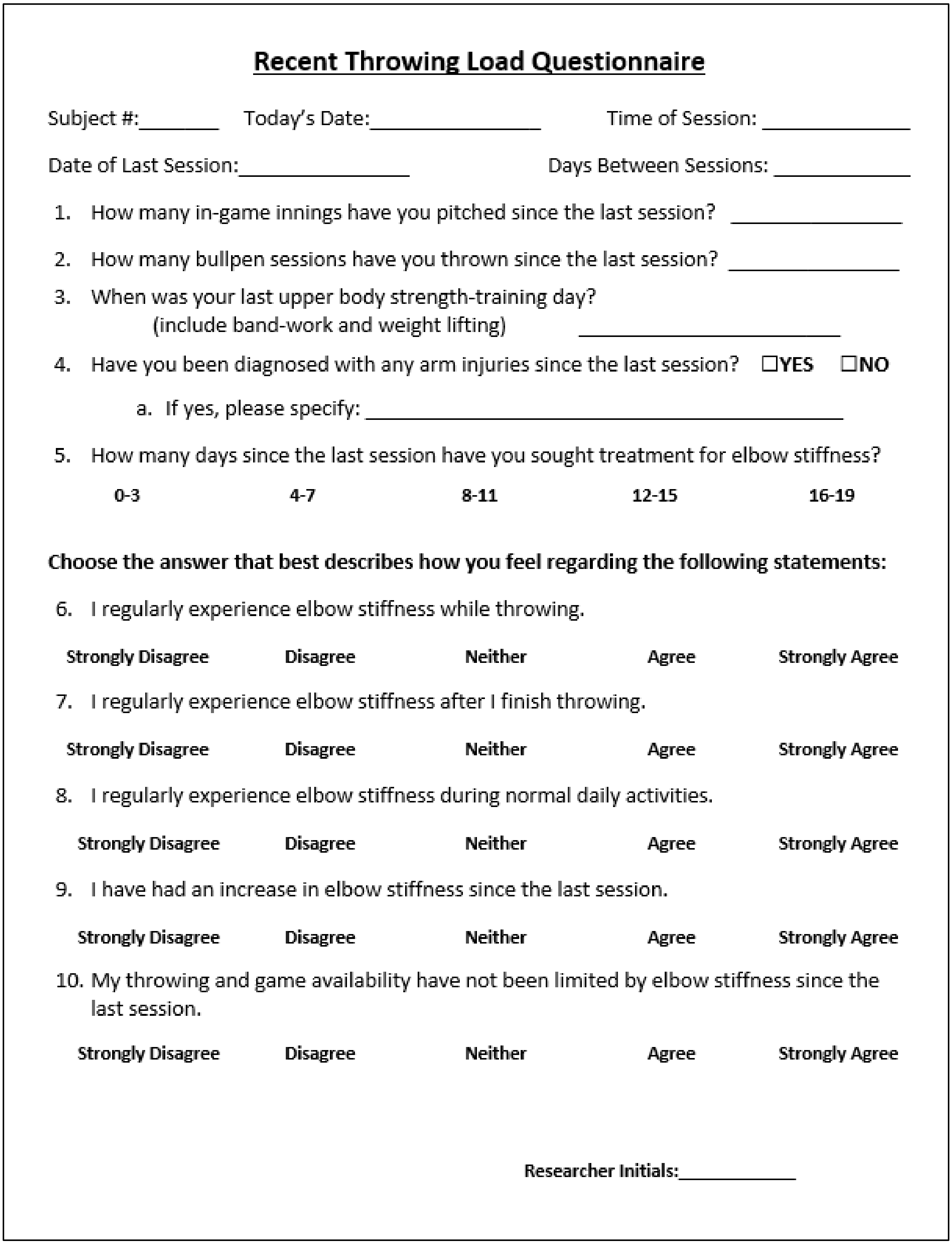
If yes, please describe______________________________ **Year**: ______

Approximately how long have you been playing competitive baseball? ______ Years

Approximately how long have you been a pitcher? ______ Years

Experimenter Initials: _______

APPENDIX B: THROWING LOAD QUESTIONNAIRE



Recent Throwing Load Questionnaire

Subject #:________ Today's Date:________________ Time of Session: ______________

Date of Last Session:________________ Days Between Sessions: _____________

1. How many in-game innings have you pitched since the last session? ________________
2. How many bullpen sessions have you thrown since the last session? ________________
3. When was your last upper body strength-training day?
   (include band-work and weight lifting) ________________________
4. Have you been diagnosed with any arm injuries since the last session? ☐**YES** ☐**NO**
   a. If yes, please specify: ____
5. How many days since the last session have you sought treatment for elbow stiffness?

0-3 **4-7** **8-11** **12-15** **16-19**

Choose the answer that best describes how you feel regarding the following statements:

6. I regularly experience elbow stiffness while throwing.

Strongly Disagree **Disagree** **Neither** **Agree** **Strongly Agree**

7. I regularly experience elbow stiffness after I finish throwing.

Strongly Disagree **Disagree** **Neither** **Agree** **Strongly Agree**

8. I regularly experience elbow stiffness during normal daily activities.

Strongly Disagree **Disagree** **Neither** **Agree** **Strongly Agree**

9. I have had an increase in elbow stiffness since the last session.

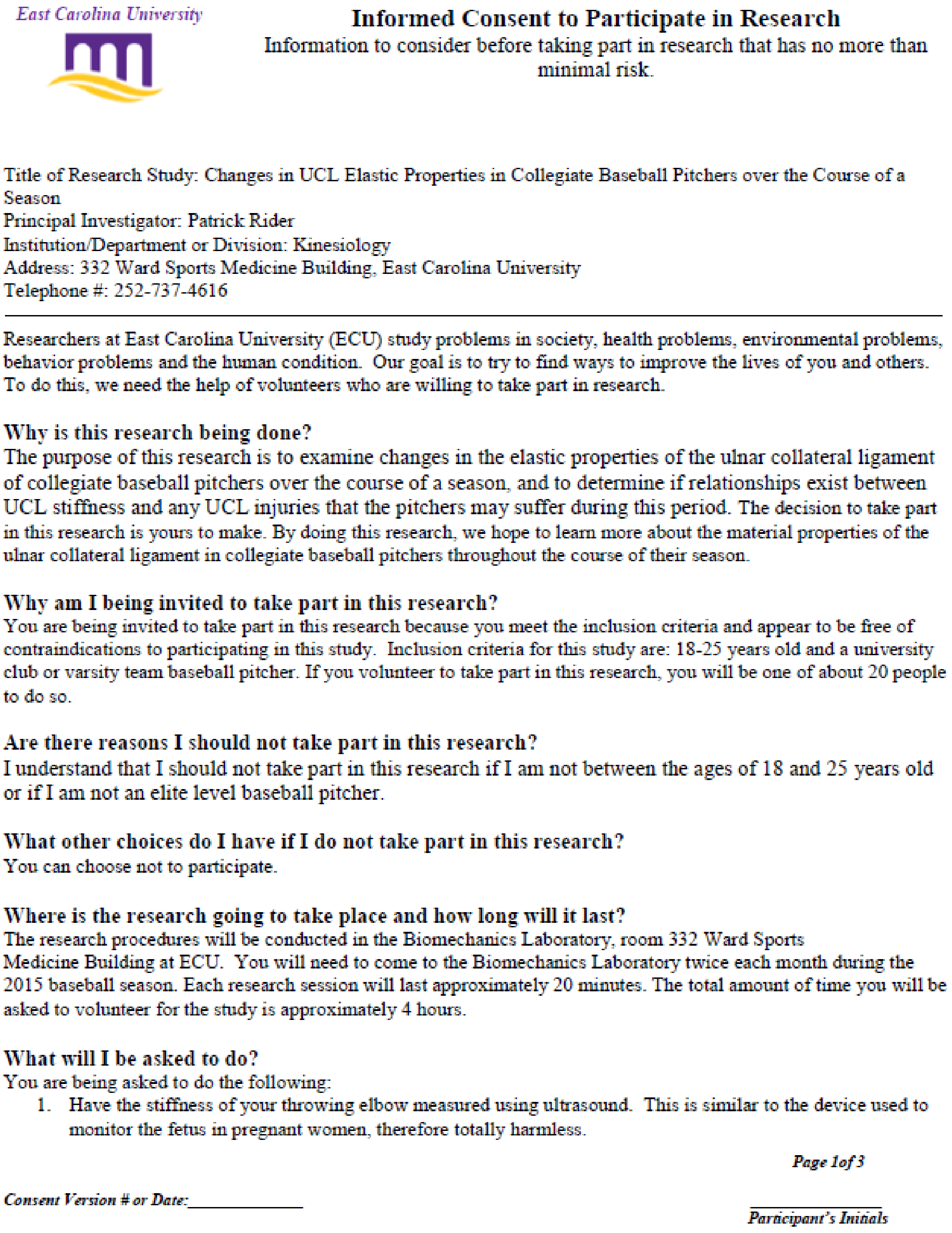
Strongly Disagree **Disagree** **Neither** **Agree** **Strongly Agree**

10. My throwing and game availability have not been limited by elbow stiffness since the last session.

Strongly Disagree **Disagree** **Neither** **Agree** **Strongly Agree**

Researcher Initials:____________

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: Changes in UCL Elastic Properties in Collegiate Baseball Pitchers over the Course of a Season
Principal Investigator: Patrick Rider
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 changes in the elastic properties of the ulnar collateral ligament of collegiate baseball pitchers over the course of a season, and to determine if relationships exist between UCL stiffness and any UCL injuries that the pitchers may suffer during this period. 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 throughout the course of their season.

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 university club or varsity team baseball pitcher. If you volunteer to take part in this research, you will be one of about 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 an elite level 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 twice each month during the 2015 baseball season. Each research session will last approximately 20 minutes. The total amount of time you will be asked to volunteer for the study is approximately 4 hours.

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.

Page 1of 3

*Consent Version # or Date:*_____________

____
Participant's Initials

2. Complete a short questionnaire each session regarding the amount of throwing you have been doing and your perception of any stiffness 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 changes that can take place in ligament tissue over time. 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.
- Patrick Rider, the primary investigator and faculty supervisor, and sub-investigators Christopher Curran and Keleigh Britt.

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.

What if I decide I do not want to continue in this research?
If you decide you no longer want to be in this research after it has already started, you may stop at any time. You will not be penalized or criticized for stopping. You will not lose any benefits that you should normally receive.

Who should I contact if I have questions?
The people conducting this study will be available to answer any questions concerning this research, now or in the future. You may contact the Faculty Coordinator, Patrick Rider at 252-737-2370 (work days between 8am and 5pm) or the lead student investigator, Christopher Curran at 252-737-4616 (work days, between 8am and 5pm).

If you have questions about your rights as someone taking part in research, you may call the Office for Reseach Integrity & Compliance (ORIC) at phone number 252-744-2914 (days, 8:00 am-5:00 pm). If you would like to report a complaint or concern about this research study, you may call the Director of the OHRI, at 252-744-1971.

I have decided I want to take part in this research. What should I do now?

The person obtaining informed consent will ask you to read the following and if you agree, you should sign this form:

- I have read (or had read to me) all of the above information.
- I have had an opportunity to ask questions about things in this research I did not understand and have received satisfactory answers.
- I know that I can stop taking part in this study at any time.
- By signing this informed consent form, I am not giving up any of my rights.
- I have been given a copy of this consent document, and it is mine to keep.

Participant's Name (PRINT)	**Signature**	**Date**

Person Obtaining Informed Consent: I have conducted the initial informed consent process. I have orally reviewed the contents of the consent document with the person who has signed above, and answered all of the person's questions about the research.

Person Obtaining Consent (PRINT)	**Signature**	**Date**

*Consent Version # or Date:*_____________

____
Participant's Initials

APPENDIX D: INSTITUTIONAL REVIEW BOARD APPROVAL

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board Office
4N-70 Brody Medical Sciences Building· Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office **252-744-2914** · Fax **252-744-2284** · www.ecu.edu/irb

Notification of Initial Approval: Expedited

From: Biomedical IRB
To: Patrick Rider
CC: Patrick Rider
Date: 11/9/2015
Re: UMCIRB 15-001577
Changes in UCL Elastic Properties in Collegiate Baseball Pitchers over the Course of a Season

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 11/6/2015 to 11/5/2016. 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
Baseball_UCL_Elastography_Consent.doc	Consent Forms
Baseball_UCL_Elastography_Protocol.docx	Study Protocol or Grant Application
Recent Throwing Load Questionnaire.pdf	Surveys and Questionnaires

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

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418