FAILURE ANALYSIS OF THE ULNAR COLLATERAL LIGAMENT FOR YOUTH BASEBALL PITCHERS

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ABSTRACT

Failure Analysis of the Ulnar Collateral Ligament for Youth Baseball Pitchers

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The objectives of this study were to (1) use kinetics from motion analysis and inverse dynamics to calculate the stress experienced by the ulnar collateral ligament (UCL) during a typical pitch cycle, (2) compare calculated maximum UCL pitching stresses to failure properties, and (3) investigate correlations between UCL stress with anthropometric and pitching biomechanical parameters. Prior motion analysis experiments of eighteen 10- to 11- year-old baseball pitchers throwing 10 fastballs were analyzed. Maximum internal elbow varus torques were calculated using inverse dynamics methods during a typical pitch cycle. Calculations used axial loading stress equations and maximum internal elbow varus torques to quantify the maximum UCL pitching stresses. UCL ultimate stresses and number of cycles to failure were calculated from prior studies with a scaling procedure to estimate youth participant values. The calculated maximum UCL pitching stresses were then compared to the estimated ultimate stresses using a paired t-test. The first major result of this study was that the maximum UCL pitching stresses were 33.83 MPa lower, on average, than the estimated ultimate stresses ($p < 0.001$). A second major result of this study was the estimated average number of cycles to failure of the UCL were 80,000+ higher, on average, than the maximum season ($p < 0.001$) and annual ($p < 0.001$) pitch counts. A third major result of this study was maximum UCL pitching stresses were significantly and positively correlated with pitch speeds, maximum shoulder external rotation torque, and maximum elbow varus torque. These results suggest 10- to 11- year-old pitchers are not likely to experience a UCL injury. The findings of this study are supported by clinical observations of elbow injuries in youth pitchers occurring primarily in other tissues.

Keywords: Baseball, Pitching, Biomechanics

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Chapter 1

INTRODUCTION

Prevalence of youth pitching arm injuries has not decreased despite the adoption of safety guidelines, pitch count recommendations, and increased media coverage of injury prevention for youth baseball pitchers [1]. Pitchers of all ages experience substantial external elbow valgus loads (Fig. 1.1) that could potentially put the elbow joint at risk of injury [2], [3]. Specifically, injury to the ulnar collateral ligament (UCL) (Fig. 1.2) is a serious and frequent injury experienced by baseball pitchers at various competitive levels. Failure of the UCL normally requires surgical repair and many months of recovery and rehabilitation [4]. For youth pitchers, such an injury could be debilitating but may be prevented with improved evidence-based injury prevention measures.

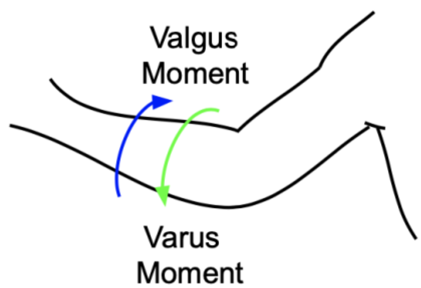

Figure 1.1: Valgus and varus moments experienced at the elbow joint during an over-head throwing activity.

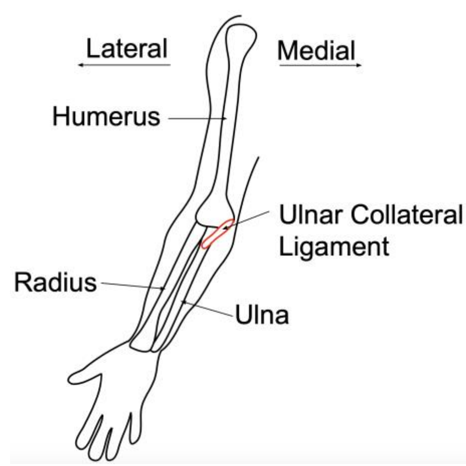

Figure 1.2: Frontal plane view of a right arm with location of the ulnar collateral ligament shown.

Common injuries such as UCL sprains have been associated with high elbow internal varus torque [5], a biomechanical mechanism of UCL-related injuries. During the pitching motion, the body is rotating the upper arm toward home plate while the inertial properties of the lower arm segment (e.g., forearm, hand, and ball) are resisting the motion, therefore creating an elbow external valgus moment (Fig. 1.1). This external valgus moment at the elbow is countered by an internal varus moment that is primarily distributed among the muscle-tendon units across the medial side of the joint and the UCL [6] (Fig. 1.2). The internal varus moment experienced by the UCL has been estimated to be at least 35% of the total varus moment at the instant of maximum external valgus load imposed by the pitching motion [2]. Prior studies have suggested 11- to 15-year-old youth pitchers are more likely to experience medial epicondyle apophysitis ("Little League Elbow") than mid-substance UCL tears [7], likely because youth pitchers have open physis (growth plate) at the medial epicondyle because the elbow does not reach skeletal maturity until approximately 15- to 16- years-old [8]. Once the growth plate at the medial epicondyle has fused with the surrounding bone at the elbow, the likely injury experienced by pitchers has been reported to be UCL tears [9]. However, it is difficult to determine when a youth pitcher is more likely to experience Little League Elbow or UCL tears because it is unknown when UCL damage begins to occur in a particular athlete.

A previous study investigated the associations between pitch counts, pitch types, and pitching mechanics with elbow and shoulder pain in young pitchers. The study followed 467 9- to 14- year-old pitchers for one season keeping pitch count logs, analyzing video of pitching mechanics and performing pre- and postseason questionnaires. The results revealed that half of the subjects experienced elbow and shoulder pain during the season and there was an increasing risk of injury with increasing cumulative pitches during the study. Thus, the study suggested that pitch counts should be limited to 75 pitches per game and 600 pitches in a season for pitchers between the ages of 9 to 14 years old [10]. Developed by USA Baseball and Major League Baseball, PitchSmart provides age-appropriate guidelines to help avoid overuse injuries for youth pitchers [11]. For 9- to 10- year-old pitchers the maximum number of pitches in a game are 75 pitches, with four days rest when pitching 66 or more pitches. For 11- to 12- year-old pitchers the maximum number of pitches in a game are 85 pitches, with four days rest when pitching 66 or more pitches. Thus, in theory, 10- and 11- year-old pitchers can throw a maximum number of 5,550 and 6,290 pitches for an entire year and 1,425 and 1,615 pitches for a three-month season. Overuse and fatigue as well as high and repetitive joint kinetics (i.e., forces and torques) are likely factors leading to elbow injuries in youth baseball pitchers.

A couple of studies have used motion analysis with inverse dynamics to analyze youth pitchers' kinetics in an attempt to identify proper biomechanics that can potentially minimize the risk of elbow injuries. These studies estimated maximum internal elbow varus torques of 28 ± 7 N-m for 23 participants (age range, 10 – 15 years) [12] and 18 ± 4 N-m for 14 participants (age, 12.1 ± 0.4 years) [3] that occurred during the cocking phase of the pitch cycle, just before maximum external shoulder rotation. Additionally, several studies have investigated kinetic and kinematic parameters correlated to external elbow valgus torque in adult baseball pitchers. One study compared body kinetics and kinematics of 69 adult pitchers (age, 20 ± 2 years; height, 180 ± 14 cm; mass, 86 ± 10 kg) using a three-dimensional motion analysis system [13]. That study concluded that six biomechanical parameters were significantly correlated ($p < 0.02$) with external elbow valgus torque: onset of trunk rotation, maximum shoulder external rotation, maximum elbow flexion time, elbow flexion at peak valgus, elbow flexion at ball release, and valgus loading rate. A separate study investigated the relationship of kinetics and kinematics of 40 professional baseball players (age, 28 ± 5 years; height, 188 ± 5 cm; mass, 90 ± 10 kg) to elbow valgus torque during a typical pitching cycle [14]. Four parameters were identified to account for 97% of the variance of elbow valgus torque: shoulder abduction angle at stride foot contact, peak shoulder horizontal adduction angular velocity, elbow angle at the instant of peak valgus stress, and peak shoulder external rotation torque. No prior studies have attempted to investigate correlations between maximum UCL pitching stresses with pitch speed or kinetic and kinematic parameters.

While kinetics linked to elbow injuries have been studied in youth pitchers, no prior studies have published mechanical and failure properties of youth UCLs for comparison. Cadaver studies have been conducted to estimate the ultimate failure properties of adult UCLs, but no studies have documented fatigue failure properties of UCLs. Ultimate failure occurs with loading to failure for one cycle, whereas fatigue failure occurs with repetitive loading at a specified number of cycles. One study utilized 10 matched elbow pairs from male human cadavers (mean age, 43 years; age range, 26-60 years) for a bone-ligament-bone experimental setup to conduct load to failure testing for intact elbows and UCL reconstruction techniques at a rate of 50% strain per second [15]. That study concluded that the intact elbows had a stiffness of 42.81 ± 11.6 N/mm and an ultimate moment of 34.0 ± 6.9 N-m. A second study tested 47 medial collateral ligaments from 37 skeletally mature rabbits to determine the strain and time behavior under static and cyclic loading over a range of applied stresses [16]. Ligaments were cycled in tension using sinusoidal loading at 1 Hz from 1N to a load corresponding to the maximum test stress. A power law curve equation was developed using the results of the study to calculate time to rupture using the ratio of applied stress to ultimate tensile stress. A third study tested eight specimens (six females and two males) for a bone-ligament-bone experimental setup to determine the mechanical properties of each component of the UCL and the palmaris longus tendon [17]. That study reported that the anterior bundle of the UCL had a cross-sectional area of 12.94 ± 3.07 mm^2 and an elastic modulus of 117.8 ± 36.9 MPa. Lastly, a fourth study determined and compared mechanical properties of the patellar tendon in adults and children utilizing imaging techniques and a knee extension experimental setup [18]. That study concluded that in 10 men (age, 28.2 ± 3.6 years) and 10 boys (age, 8.9 ± 0.7 years) the elastic modulus of the patellar tendons was significantly different ($p < 0.01$) at 597.4 ± 28.5 MPa and 254.7 ± 42.3 MPa, respectively.

Failure stresses and stress-strain responses of ligaments are highly dependent on loading conditions because of their viscoelastic properties. Cadaver studies have been conducted to investigate the viscoelastic properties and behavior of ligaments. However, no prior studies have investigated the viscoelastic properties of UCLs in adults or youths. A prior study compared the viscoelastic properties of tibial collateral, anterior cruciate and posterior cruciate ligaments using tensile load to failure testing at two strain rates [19], [20]. That study concluded the anterior cruciate ligament failed at loads of 48.2 ± 2.8 kg and 63.8 ± 2.3 kg at strain rates of 40% per second and 140% per second, respectively.

There are a limited number of studies which have investigated failure stresses and/or strains in the soft tissues that may be injured in youth pitchers. One study of 14 elite youth baseball pitchers (age, 12.1 ± 0.4 years) compared humeral torsional stresses to estimate failure properties for epiphyseal cartilage [21]. That study concluded that maximum shear stress from the high shoulder external rotation torque was more than 400% of the failure stress of the epiphyseal cartilage. That conclusion suggests that continuous superficial damage of the growth plate cartilage (i.e., "little league shoulder") occurs during repetitive pitching and indicates the importance of rest allocation to avoid fatigue injury. No prior studies with youths have been conducted that linked pitching arm kinetics to UCL damage using UCL mechanical properties (e.g., elastic modulus and ultimate stress).

The goals of this current study were to calculate maximum UCL pitching stresses and investigate relations with failure properties and underlying biomechanical mechanisms. The hypotheses were that, for 10- to 11- year-old pitchers, (1) the maximum UCL pitching stresses due to internal elbow varus torque would be lower than estimated UCL ultimate stresses, (2) estimated UCL number of cycles to failure would be higher than maximum season and annual pitch counts, and (3) UCL pitching stresses would be significantly correlated to anthropometric and pitching biomechanical parameters. To address these hypotheses, the specific aims were to (1) calculate maximum UCL varus torques, (2) calculate maximum UCL loads and stresses using mechanical properties estimated from published data, (3) calculate injury risk ratios (IRRs) for ultimate failure, (4) calculate the number of cycles to failure for the UCL, and (5) use linear regression models to investigate correlations between maximum UCL pitching stresses with anthropometric, pitch speed, kinetic, and kinematic parameters.

Chapter 2

METHODS

2.1 Participant Recruitment and Informed Consent

Motion capture data were available from a previous youth pitching study [22], [23]. 18 male participants (age, 10.6 ± 0.5 years; height, 147.8 ± 7.4 cm; body mass, 39.6 ± 7.3 kg; body mass index (BMI), 18.0 ± 2.2 kg/m^2) with prior pitching experience and no recent history of pitching-related injuries were chosen for participation. Experimental protocols were approved by Cal Poly's Institutional Review Board and were designed to minimize risk to human subjects. Informed assent and consent were obtained from each participant and their legal guardian, respectively.

2.2 Experiments

Pitching experiments were completed and captured using a motion analysis system. Six Owl, three Osprey, two Eagle, and one Kestrel digital cameras (Motion Analysis, Santa Rosa, CA, USA) were used to track reflective markers. Participants were asked to complete warm-up exercises and change into compression clothing, and 38 retroreflective markers were placed on participant according to the PitchTrak software (Motion Analysis) marker set. The markers were separated into two groups: anatomical markers placed at specific landmarks, and tracking markers arbitrarily placed on a segment. Marker trajectories were recorded in Cortex Analysis software (Motion Analysis) at 200 Hz, interpolated (third-order spline), and filtered (4^{th} order Butterworth filter, cut-off frequency 12 Hz) [24]. Prior to dynamic motion capture, a static pose motion capture was conducted in order to calculate joint positions and segment lengths. Experimental setup consisted of participants pitching off a portable mound (six-inch height) in the room's center into a net 23 feet away with a scaled strike zone. 10 fastball pitches were recorded per participant and the last three pitches with usable data were analyzed independently to obtain averaged values.

2.3 Kinetics

All kinetic parameters were calculated in PitchTrak Software (Motion Analysis) using segment inertial parameters (SIPs) for each participant. Pitching SIPs (e.g., mass, center of mass, and radius of gyration of the upper arm, forearm, and hand) were determined for each participant using a developed MATLAB (MathWorks, Natick, MA, USA) script and dual energy x-ray absorptiometry (DXA) data [22], [23]. The use of participant specific SIPs, derived from the youths' anthropometry, leads to more accurate predictions of injury-related kinetics, and thus, UCL stress. Analyzed kinetic parameters included the maximum value of internal elbow varus torque through the pitch cycle, which was defined from front foot contact to ball release. Front foot contact was determined when the front foot segment stopped moving and ball release was determined based on the wrist pronation during the pitch. Kinetic parameters were expressed as internal joint loads (e.g., an elbow external valgus torque produces an elbow internal varus torque generated by muscle and ligaments including the UCL [2]).

2.4 Analysis

To quantify the kinetics experienced by the UCL, a novel analysis was conducted to study maximum UCL pitching stresses occurring at maximum elbow internal varus torque. There is a scarcity of data for relevant UCL mechanical properties (e.g., elastic modulus, fatigue stress, ultimate stress, and cross-sectional areas) representing the study population (i.e., 10- to 11- year-old youth baseball pitchers). Thus, several assumptions including scaling ratios between youth and adult parameters were used to determine the required UCL mechanical properties for youth pitchers.

2.4.1 Maximum Ulnar Collateral Ligament Stress

The maximum elbow internal varus torque during the pitch cycle was extracted from the PitchTrak software analysis and used to estimate the elbow internal varus torque experienced by the UCL (i.e., the UCL torque). Based on prior research, that UCL torque was calculated as 35%

of the elbow internal varus torque [2]. In order to interpret the UCL torque in the context of failure, the UCL torque was used to estimate maximum UCL pitching stresses in the following steps.

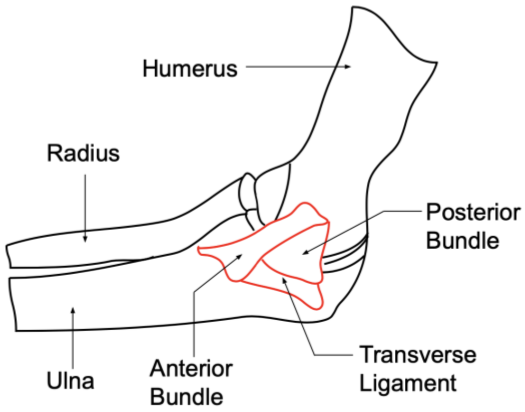

Figure 2.1: Insertion and origin points for ulnar collateral ligament.

First, the UCL torque M was divided by an estimated moment arm d to calculate the UCL force F using

$$F = \frac{M}{d}\,. \tag{1}$$

The moment arm was approximated using the medial epicondyle insertion point of the UCL with respect to the center of the radiocapitellar joint (i.e., the point of articulation during over-head throwing activity). A study with cadaver ligaments (seven females and three males; mean age, 46 years) reported an average moment arm of 39 ± 3.89 mm for 10 test specimens [25]. The UCL moment arm was assumed to correlate linearly with height similar to a prior study with patellar tendon moment arms of adults and children [26]. Eq. (2) was used to develop a scaling factor S_1 for each participant using the height of the participant $h_{participant}$ of this current study and the estimated average height $\bar{h}_1$ of the cadaver study [25].

$$S_1 = \frac{h_{participant}}{\bar{h}_1}\,. \tag{2}$$

The average heights of the participants from the cadaver study were estimated utilizing available age and/or gender information [27]. Scaling factor S_1 was then multiplied by the average moment arm (i.e., 39 mm) from the cadaver study to get an average moment arm for each participant.

Second, the maximum UCL pitching stress σ was calculated by dividing F by and the average cross-sectional area A of the UCL using

$$\sigma = \frac{F}{A}. \tag{3}$$

The anterior bundle of the UCL is considered to be the primary stabilizer of the external valgus torque experienced by the UCL [28], [29]. Thus, it was assumed that the stress caused by the UCL torque was experienced by the anterior bundle. A study reported the average cross-sectional area of the UCL's anterior bundle to be 12.94 ± 3.07 mm^2 [17]. UCL cross-sectional area was assumed to correlate linearly with height similar to a prior study with ACL cross-sectional areas of youths (3- to 18- years old) [30]. Eq. (4) was used to develop an additional scaling factor for each participant using the height of the participant $h_{participant}$ of this current study and the estimated average height $\bar{h}_2$ of the cadaver study [17].

$$S_2 = \frac{h_{participant}}{\bar{h}_2} \tag{4}$$

The average height of the participants from the cadaver study was estimated utilizing available age and/or gender information [27]. Scaling factor S_2 was then multiplied by the average cross-sectional area (i.e., 12.94 mm^2) from the cadaver study to get an average cross-sectional area for each participant.

2.4.2 Ulnar Collateral Ligament Strain

The UCL strain was calculated by dividing σ by the elastic modulus E using

$$\epsilon = \frac{\sigma}{E}\,. \tag{5}$$

The strain was calculated using Generalized Hooke's law with the assumption the ligament is only experiencing axial tension in a one-dimensional stress state. The UCL elastic modulus has been reported to be 117.8 ± 36.9 MPa from prior studies with cadaver ligaments [17]. UCL elastic modulus was assumed to correlate linearly with age similar to a prior study with patellar tendons of men and boys [18]. Eq. (6) was used to develop an additional scaling factor for each participant using the age of the participant $n_{participant}$ of this current study and elastic modulus of boys E_{boys}, elastic modulus of men E_{men}, and age of boys n_{boys} from a previous study [18].

$$S_3 = \left(\frac{E_{boys}}{E_{men}}\right) * \left(\frac{n_{participant}}{n_{boys}}\right) \tag{6}$$

The scaling factor S_3 was then multiplied by the estimated average elastic modulus (i.e., 117.8 MPa) from the cadaver study to get an average elastic modulus for each participant.

Strain rates were calculated for every participant using strains calculated by Eq. (5) then divided by the time taken from front foot contact to maximum internal varus torque to calculate strain rates for each participant.

2.4.3 Ulnar Collateral Ligament Failure Stress

The calculated maximum pitching stresses, which represent maximum values during repetitive loading, were compared to estimated UCL ultimate stresses. UCL ultimate stresses were approximated using values from previous studies with cadaver ligaments. A prior study reported the ultimate moment of the UCL to be 34.0 N-m [15]. Youth failure properties were assumed to scale roughly the same way as age and elastic modulus due to lack of published values. Thus, the scaling factor S_3 was then multiplied by the estimated average ultimate moment (i.e., 34.0 N-m) from a previous cadaver study to get an average ultimate moment M_{ult} for each participant. The UCL ultimate stress σ_{ult} was calculated for every participant using M_{ult}, d, and A using

$$\sigma_{ult} = \left(\frac{M_{ult}}{d}\right) * \left(\frac{1}{A}\right). \tag{7}$$

For comparison, an injury risk ratio (IRR) was calculated for every participant using σ and ultimate stress σ_{ult} using

$$IRR = \frac{\sigma}{\sigma_{ult}}. \tag{8}$$

2.4.4 Number of Cycles to Failure

A prior study developed a power law curve equation to determine time to rupture of rabbit MCLs under tensile loading [16]. Using the reported equation and loading frequency of 1 Hz, Eq. (10) was developed for number of cycles to failure. The number of cycles to failure N of the UCL was calculated using σ and σ_{ult} using

$$N = (7.42 \text{ x } 10^9) * \left(\frac{\sigma}{\sigma_{ult}} * 100\right)^{-3.72}. \tag{9}$$

The estimated number of cycles to failure would be considered a worst-case scenario because it is assuming a continuous pitching frequency of one pitch per second.

2.4.5 Correlations Between Maximum UCL Pitching Stress and Pitching Biomechanical Parameters

Prior studies have investigated associations between pitching kinetic and kinematic parameters with external elbow valgus torque in adult and professional baseball pitchers [13], [14]. Also, prior studies have investigated associations between BMI and kinetic parameters associated with external elbow varus torque for 9- to 12- year-old pitchers [3], [31]. Such parameters correlated with external elbow valgus torque from prior studies were investigated in this study to compare with maximum UCL pitching stresses. The anthropometric parameters were the following: body mass, body height, BMI, total arm mass and lower arm (i.e., forearm and hand) mass. The pitching biomechanical parameters were the following: pitch speed, maximum shoulder external rotation, elbow flexion at maximum elbow varus torque, elbow flexion at ball release, shoulder abduction angle at foot contact, maximum shoulder external rotation torque, maximum elbow varus torque, stride length at foot contact, front foot position at foot contact, and max trunk rotation timing. Stride length, front foot position, and max trunk rotation timing were calculated using standard techniques from a prior studies [13], [32].

2.5 Statistics

To test the first hypothesis, a paired t-test between maximum UCL pitching stresses and calculated ultimate stresses for each participant was performed. To test the second hypothesis, a paired t-test between average number of cycles to failure with average recommended season and maximum annual pitch counts was performed. To test the third hypothesis, correlations between anthropometric parameters and relevant pitching biomechanical parameters with maximum UCL pitching stresses were analyzed using single variable linear regression models. Significance levels were defined by $p < 0.05$.

Chapter 3

RESULTS

A summary of UCL dimensional and mechanical properties, kinetics, and stresses for 10- to 11- year-old pitchers are listed in Tables 3.1, 3.2, and 3.3. The average UCL maximum stress, 10.89 ± 2.92 MPa, was lower and significantly different from the average UCL ultimate stress, 44.72 ± 4.15 MPa ($p < 0.001$) (Fig. 3.1). The average UCL IRR (maximum pitching stress divided by ultimate stress) was 0.25 ± 0.07, with a range of 0.16 to 0.43 (Table 3.3). An average number of cycles to failure of 87,085 ± 84,278, with a range of 6,369 to 273,996, was higher and significantly different than the maximum season and annual pitch counts of 1,615 ($p < 0.001$) and 6,290 pitches ($p < 0.001$), respectively (Table 3.3). Refer to Appendix A for calculated values for each participant.

Table 3.1. Estimated ulnar collateral ligament dimensional properties (mean ± 1 SD).

Moment Arm (mm)	Cross-Sectional Area (mm^2)
34.64 ± 1.74	11.61 ± 0.58

Table 3.2. Estimated ulnar collateral ligament kinetics, stresses, and strains (mean ± 1 SD).

Elbow Varus Torque (N-m)	UCL Torque (N-m)	UCL Force (N)	UCL Pitching Stress (MPa)	UCL Strain (mm/mm)	UCL Strain Rate (% s^{-1})
12.59 ± 4.11	4.41 ± 1.44	126.67 ± 38.89	10.89 ± 2.92	0.175 ± 0.050	98 ± 33

Table 3.3. Estimated ulnar collateral ligament mechanical and failure properties (mean ± 1 SD).

Elastic Modulus (MPa)	Ultimate Moment (N-m)	Ultimate Force (N)	Ultimate Stress (MPa)	IRR	No. of Cycles
61.93 ± 1.83	17.88 ± 0.53	517.03 ± 24.53	44.72 ± 4.15	0.25 ± 0.07	87085 ± 84278

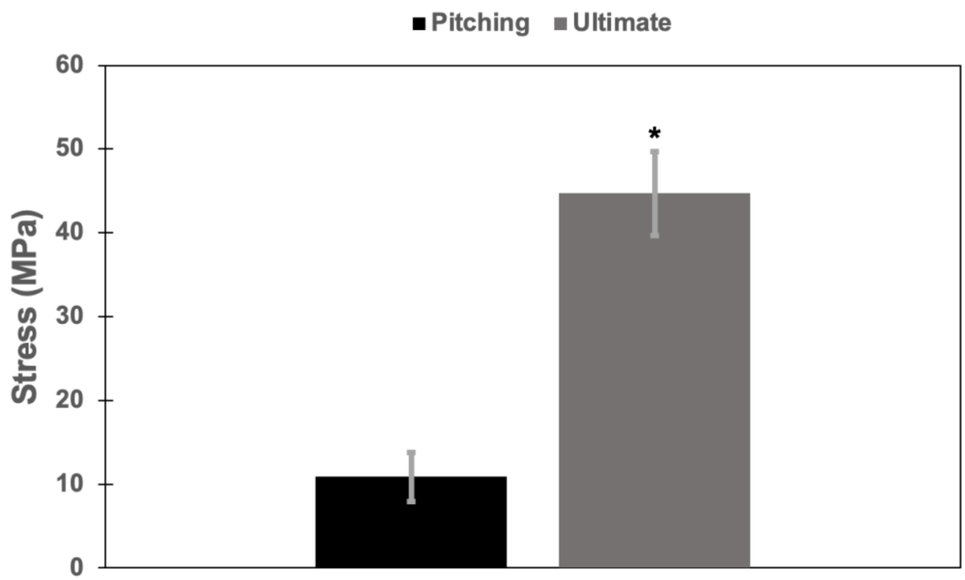

Figure 3.1: Youth participant's ulnar collateral ligament maximum and ultimate stress (mean ± 1 SD). * = significant difference when compared to maximum pitching stress, $p < 0.001$.

UCL maximum pitching stresses were positively correlated with pitch speed ($p = 0.007$), maximum shoulder external rotation torque ($p = 0.018$), and maximum elbow varus torque ($p < 0.001$) (Table 3.4). No associations were found between UCL stresses and anthropometric or other pitching biomechanical parameters. Refer to Appendix B for statistical analysis of all parameters studied.

Table 3.4. Single linear regression results of ulnar collateral ligament maximum stresses vs. anthropometric and pitching biomechanical parameters. *= significant correlation; $p < 0.05$ denotes significance. †= linear regression analysis done with data from eleven of the eighteen participants.

Explanatory Variable	Mean ± SD	R^2	P-value
Body Height (cm)	147.9 ± 7.4	0.0254	0.528
Body Mass (kg)	39.6 ± 7.3	0.0186	0.59
BMI (kg/m^2)	18.0 ± 2.2	0.0130	0.652
Total Arm Mass (kg)	2.20 ± 0.48	0.0208	0.568
Lower Arm Mass (kg)	0.85 ± 0.15	0.0443	0.402
Pitch Speed (mph)	57.1 ± 3.9	0.3776	0.007*
Maximum Shoulder External Rotation (deg)	157.1 ± 29.6	0.0292	0.498
Elbow Flexion at Maximum Internal Elbow Valgus Torque (deg)	79.5 ± 19.7	0.0116	0.498
Elbow Flexion at Ball Release (deg)	28.2 ± 11.8	0.0209	0.567
Shoulder Abduction at Front Foot Contact (deg)	83.1 ± 14.1	0.0005	0.930
Maximum Shoulder External Rotation Torque (N-m/BW-H)	0.032 ± 0.009	0.3010	0.018*
Maximum Elbow Varus Torque (N-m/BW-H)	0.022 ± 0.006	0.7958	<0.001*
Stride Length (% of BH)	83.1 ± 4.9	0.0498	0.374
Front Foot Position (cm)	5.2 ± 12.1	0.0272	0.513
Max Trunk Rotation Timing (% of PC) †	8.2 ± 23.0	0.2829	0.092

Chapter 4

DISCUSSION

The results support the first hypothesis that, for 10- to 11- year-old pitchers, the UCL maximum pitching stresses due to maximum internal elbow varus torque were 33.83 MPa lower, on average, and statistically different than the UCL ultimate stresses. In addition, the average IRR of the 10- to 11- year-old pitchers was 0.25. One possible explanation for this is that baseball pitchers likely do not experience UCL ruptures due to a single pitch, but rather experience continuous damage from repetitive pitching without proper rest allocation [28]. A previous study suggested that the torque experienced by the UCL during a typical pitch cycle is 34.6 N-m, similar to the reported UCL moment prior to failure of 32.1 ± 9.6 N-m in that study [29], resulting in an average IRR of 1.08 and predicting failure. There are several reasons for the discrepancy regarding IRRs reported in this study and those of [29]. First, the prior study used 26 highly skilled adult male pitchers with a mean age of 22 ± 2.3 years, which is considerably higher than the age of this current study, 10.6 ± 0.5 years. Second, the previous study with adult pitchers reported significantly larger maximum internal elbow varus torque of 64 ± 12 N-m compared to 12.59 ± 4.11 N-m of this study. Third, the previous study assumed the UCL provided 54% of the internal varus torque [29]. This study assumed the UCL provided 35% of the internal elbow varus torque because of another study that accounted for the dynamic stabilizations of muscle and tendon contributions to internal elbow varus torque [2].

The results support the second hypothesis that, for 10- to 11- year-old pitchers, the number of cycles to failure are at least 80,000+ higher, on average, and statistically different than the maximum season and annual pitch counts. The number of cycles would be assumed if the UCL were to experience continuous loading at one pitch per second. This would be a conservative estimate because it does not consider the time between pitches in a game and the mandated rest needed after a certain number of pitches thrown in an organized setting [11]. The average UCL number of cycles to failure of 87,085 is 54 times the maximum season pitch counts and 14 times the maximum annual pitch counts. One possible explanation for this result is that UCL fatigue damage is not common in 10- to 11- year-old pitchers, who are likely to experience other elbow injuries. Indeed, the findings of this current study are consistent with previous clinical observations regarding injuries experienced by 10- to 11- year-old pitchers. The most common injury experienced by youth pitchers is Little League Elbow due to a relatively weak growth plate and repetitive stresses imposed by the dynamic stabilizers during a pitch cycle [7]. Both the UCL and forearm flexor-pronator muscles originate from the medial epicondyle and are the primary dynamic stabilizers to the external valgus torque imposed by a typical pitching motion. The UCL and tendon loads at the bone insertion points are the likely causes of the repetitive microtrauma experienced by the growth plate [9]. Thus, the results of this study and prior observations suggest that without the proper measures taken for injury prevention, it is likely a pitcher will experience elbow pain or serious injury to their elbow growth plate before they damage the UCL.

The results support the third hypothesis that, for youth pitchers, the maximum UCL pitching stresses are significantly related to anthropometric and pitching biomechanical parameters. Positive associations were found between maximum UCL pitching stress with pitch speed, maximum shoulder external rotation torque, and maximum elbow varus torque. Regarding pitch speed, this finding agrees with a previous study that reported differences in pitch speed between youth baseball pitchers with and without medial elbow pain [33]. That study found that 15 pitchers (mean age, 11.3 ± 0.6 years) with pain and 15 pitchers (mean age, 11.1 ± 1.0 years) without pain had significantly different ($p < 0.006$) pitch speeds at 24.8 ± 2.7 m/s and 23.0 ± 2.7 m/s, respectively. A possible explanation for this result is that youth pitchers with higher pitch speeds generate larger internal elbow varus torques than those with lower pitch speeds. Also, in this study a linear regression model predicted that maximum internal elbow varus torque explained approximately 80% of variance (i.e., R^2) of maximum UCL pitching stresses. Thus, this finding agrees with prior studies suggesting high internal elbow varus torque is a primary biomechanical mechanism of common pitching injuries such as UCL sprains and medial elbow pain [5], [12], [34].

The current study provides several clinical implications for youth baseball pitchers. This study appears to be the first to compare maximum UCL pitching stresses and UCL ultimate stresses. The results of this study agree with prior clinical observations of 10- to 11- year-old pitchers that the growth plate is the weakest structure in the elbow and more prone to injury than the UCL. Future studies with older baseball pitchers (16 years or older), if found to have a higher IRR than this current study, should focus on obtaining more accurate pitch counts because a prior study suggested approximately 42% of all pitches from a high school varsity starter were not accounted for in pitch count monitoring [35]. Warm-up and bullpen activity are not accounted for in pitch counts but are considered to be a substantial volume of pitches, suggesting the importance of monitoring additional pitches to help mitigate the risk of fatigue injuries.

A second clinically relevant aspect of this study was the focus on IRRs for the UCL of 10- to 11- year-old pitchers. To further improve injury risk predictions of elbow injuries among baseball pitchers, IRRs can be calculated for ligaments and when applicable to growth plate cartilage. This additional information would allow for further development and more specific injury prevention measures and understanding of likely failure points. Furthermore, the application of IRRs for different tissue components can be applied to pitchers of all ages and other extremities prone to injuries due to high and repetitive joint kinetics.

There are several limitations to this study. First, due to lack of published data, several scaling factors were assumed that introduced errors into the analysis. In particular, scaling factors were assumed to calculate the UCL torque from the total internal elbow varus torque and to calculate UCL dimensional and mechanical properties for youths from their respective values for adults. Second, the maximum UCL pitching stresses could not be compared to UCL fatigue stresses because of a lack of published data. Considering the time between pitches and rest between games for pitchers would make the calculated maximum UCL pitching stresses difficult to compare to a fatigue stresses because fatigue stress is determined with a continuous cyclic load to a number of cycles to failure. Third, this study did not consider the loading conditions (i.e., strain rate) of a typical pitch cycle when estimating UCL ultimate stresses. The average linear strain rate of this study, 98% per second, was higher than the strain rate, 50% per second, used to estimate the UCL ultimate moment of a prior study [15], thus suggesting a conservative value for UCL ultimate stresses and IRRs. The UCL ultimate moment would be expected to be substantially larger at a higher strain rate similar to the findings of [19], however no attempt was made to scale the UCL ultimate moment due to lack of published data. Furthermore, it would be expected the strain rate experienced by the UCL during a typical pitch cycle to be non-linear. Fourth, the UCL was assumed to be an elastic material to calculate strains and strain rates. Viscoelastic equations and properties would be required to better estimate the stress and strain behavior of the UCL. Fifth, no attempt was made to calculate the stress occurring at the medial epicondylar physis (Fig. 4.1) and, thus, this study did not address the risk for Little League Elbow. A prior study [21] calculated the shear stresses at the proximal humeral physis using simple stress equations, however that is not applicable in this study. The location of the medial epicondyle growth plate and loading from the UCL and muscle-tendon units make the analysis much more complex. To address this common injury, a more sophisticated approach must be implemented such as finite element analysis.

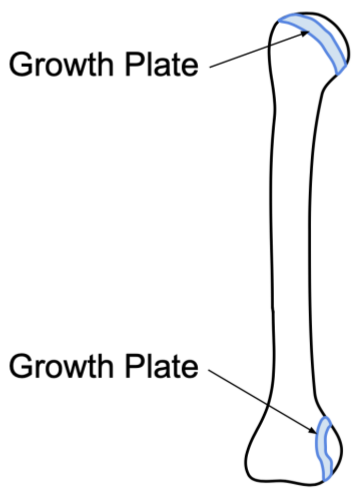

Figure 4.1: Locations of proximal humeral physis (top) and medial epicondyle physis (bottom).

In summary, this study had several novel methods and results. First, this appears to be the first study to use motion analysis, inverse dynamics, and scaling procedures to estimate the maximum UCL pitching stress. Second, this study used a scaling procedure to estimate UCL ultimate stresses for comparison with maximum UCL pitching stresses. Third, the number of cycles to failure were estimated using maximum and ultimate UCL pitching stresses. Fourth, this study used linear regression models to investigate correlations between maximum UCL pitching stress with anthropometric parameters, pitch speed, and kinetic and kinematic parameters. Fifth, the main results were that UCL failure was not predicted for 10- to 11- year-old pitchers and maximum UCL pitching stresses have the strongest non-kinetic associations with pitch speed. Agreeing with clinical observations of elbow injuries in 10- to 11- year-old pitchers occurring primarily at the growth plate. Future studies should consider the use of advanced imaging techniques (e.g., magnetic resonance imaging, ultrasound scans, etc.) and conduct cadaver ligament experiments to better estimate UCL mechanical properties of youths. More complex analyses (e.g., finite element analysis, viscoelastic models) could be considered to study the stresses occurring at the growth plate of youth pitchers and UCL of older pitchers to address the risk of common elbow injuries. Furthermore, fatigue IRR predictions and number of cycles to failure should be attempted for older pitchers, who are more susceptible to UCL injuries, to improve evidence-based pitch counts over a season or year.

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Appendix A: Participant-Specific Scaling Factors and Values

Table A.1. Complete participant-specific scaling factors for ulnar collateral ligament dimensional and mechanical parameters.

Participant	Moment Arm	Cross-Sectional Area	Elastic Modulus	Ultimate Moment
2018 Nov 09-02	0.915	0.925	0.541	0.541
2018 Nov 07-01	0.931	0.941	0.523	0.523
2018 Aug 16-01	0.905	0.914	0.543	0.543
2018 Aug 15-01	0.821	0.829	0.531	0.531
2018 Aug 13-01	0.836	0.845	0.530	0.530
2018 Aug 01-02	0.889	0.899	0.526	0.526
2017 Sep 30-01	0.937	0.947	0.547	0.547
2017 Sep 07-02	0.868	0.877	0.521	0.521
2017 Aug 20-03	0.913	0.922	0.504	0.504
2017 Aug 20-02	0.841	0.850	0.501	0.501
2017 Aug 20-01	0.841	0.850	0.535	0.535
2017 Jul 27-02	0.874	0.883	0.501	0.501
2017 Jul 27-01	0.931	0.941	0.537	0.537
2017 Jul 26-01	0.949	0.959	0.535	0.535
2017 Jul 21-02	0.838	0.846	0.495	0.495
2017 Jul 21-01	0.868	0.877	0.533	0.533
2017 Jul 19-02	0.862	0.871	0.527	0.527
2017 Jul 19-01	0.969	0.979	0.532	0.532

Table A.2. Complete participant-specific ulnar collateral ligament dimensional parameters, kinetics, and maximum pitching stresses.

Participant	Moment Arm (mm)	Cross-Sectional Area (mm^2)	UCL Torque (N-m)	UCL Force (N)	UCL Pitching Stress (MPa)	UCL Strain (mm/mm)	UCL Strain Rate (% s^{-1})
2018 Nov 09-02	35.70	11.97	7.86	220.28	18.41	0.289	160
2018 Nov 07-01	36.31	12.17	4.13	113.88	9.36	0.152	71
2018 Aug 16-01	35.28	11.83	4.75	134.74	11.39	0.178	96
2018 Aug 15-01	32.01	10.73	4.23	132.11	12.31	0.197	106
2018 Aug 13-01	32.60	10.93	5.09	156.26	14.30	0.229	124
2018 Aug 01-02	34.69	11.63	5.03	144.93	12.46	0.201	133
2017 Sep 30-01	36.54	12.25	4.99	136.61	11.15	0.173	71
2017 Sep 07-02	33.85	11.35	4.47	132.17	11.65	0.190	98
2017 Aug 20-03	35.60	11.93	4.00	112.46	9.42	0.159	79
2017 Aug 20-02	32.79	10.99	2.67	81.57	7.42	0.126	71
2017 Aug 20-01	32.79	10.99	2.83	86.15	7.84	0.124	88
2017 Jul 27-02	34.08	11.42	4.01	117.61	10.29	0.174	108
2017 Jul 27-01	36.31	12.17	3.94	108.55	8.92	0.141	69
2017 Jul 26-01	37.01	12.41	7.16	193.57	15.60	0.248	149
2017 Jul 21-02	32.68	10.95	3.38	103.41	9.44	0.162	103
2017 Jul 21-01	33.85	11.35	2.90	85.80	7.56	0.120	85
2017 Jul 19-02	33.61	11.27	3.67	109.31	9.70	0.156	89
2017 Jul 19-01	37.78	12.66	4.18	110.58	8.73	0.139	59

Table A.3. Complete participant-specific ulnar collateral ligament failure kinetics, stresses, injury risk ratios, and number of cycles to failure.

Participant	Elastic Modulus (MPa)	Ultimate Moment (N-m)	Ultimate Load (N)	Ultimate Stress (MPa)	IRR	No. of Cycles
2018 Nov 09-02	63.77	18.40	515.58	43.09	0.43	6369
2018 Nov 07-01	61.62	17.79	489.88	40.25	0.23	61280
2018 Aug 16-01	63.99	18.47	523.52	44.27	0.26	41966
2018 Aug 15-01	62.58	18.06	564.32	52.59	0.23	59692
2018 Aug 13-01	62.41	18.01	552.52	50.56	0.28	29554
2018 Aug 01-02	61.96	17.88	515.59	44.34	0.28	30233
2017 Sep 30-01	64.39	18.58	508.58	41.52	0.27	35793
2017 Sep 07-02	61.40	17.72	523.56	46.14	0.25	45092
2017 Aug 20-03	59.42	17.15	481.71	40.36	0.23	60310
2017 Aug 20-02	59.03	17.04	519.52	47.26	0.16	263888
2017 Aug 20-01	62.98	18.18	554.29	50.42	0.16	273997
2017 Jul 27-02	59.03	17.04	499.89	43.76	0.24	58603
2017 Jul 27-01	63.32	18.27	503.34	41.36	0.22	81012
2017 Jul 26-01	63.03	18.19	491.58	39.62	0.39	8628
2017 Jul 21-02	58.27	16.82	514.66	46.99	0.20	105415
2017 Jul 21-01	62.81	18.13	535.59	47.20	0.16	244841
2017 Jul 19-02	62.13	17.93	533.47	47.34	0.20	97986
2017 Jul 19-01	62.70	18.10	478.97	37.82	0.23	62874

Appendix B: Ulnar Collateral Ligament Stress Statistical Analysis

Regression Analysis: UCL Operating Stress versus Body Height

Regression Equation

UCL Operating Stress = 1.6 + 0.0626 Body Height

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.6	14.4	0.11	0.912	
Body Height	0.0626	0.0971	0.65	0.528	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.97296	2.54%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	3.682	3.682	0.42	0.528
Body Height	1	3.682	3.682	0.42	0.528
Error	16	141.416	8.839		
Lack-of-Fit	13	132.867	10.221	3.59	0.160
Pure Error	3	8.549	2.850		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.41	11.17	7.24	2.54	R

R Large residual

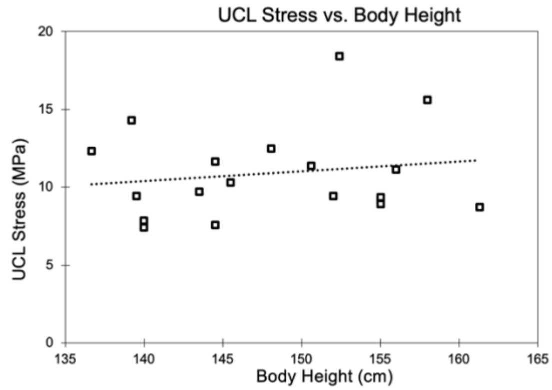


Figure B.1: Linear regression statistics and plot for ulnar collateral ligament stress vs. body height.

Regression Analysis: UCL Operating Stress versus Body Mass

Regression Equation

UCL Operating Stress = 8.73 + 0.0544 Body Mass

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	8.73	3.98	2.19	0.043	
Body Mass	0.0544	0.0989	0.55	0.590	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.98331	1.86%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	2.696	2.696	0.30	0.590
Body Mass	1	2.696	2.696	0.30	0.590
Error	16	142.402	8.900		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.41	10.97	7.44	2.57	R
7	11.15	11.91	-0.76	-0.34	X

R Large residual
X Unusual X

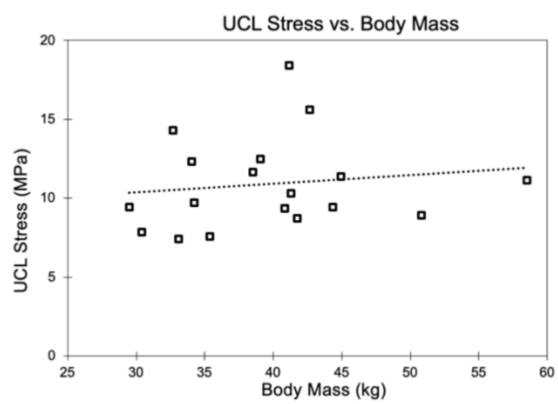


Figure B.2: Linear regression statistics and plot for ulnar collateral ligament stress vs. body mass.

Regression Analysis: UCL Operating Stress versus BMI

Regression Equation

UCL Operating Stress = 8.17 + 0.151 BMI

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	8.17	5.95	1.37	0.189	
BMI	0.151	0.329	0.46	0.652	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.99179	1.30%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	1.885	1.8848	0.21	0.652
BMI	1	1.885	1.8848	0.21	0.652
Error	16	143.213	8.9508		
Lack-of-Fit	15	142.835	9.5223	25.16	0.155
Pure Error	1	0.378	0.3784		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.41	10.86	7.55	2.60 R	
7	11.15	11.72	-0.57	-0.25	X

R Large residual
X Unusual X

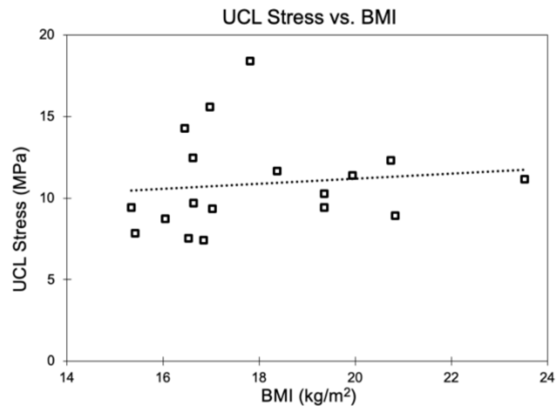


Figure B.3: Linear regression statistics and plot for ulnar collateral ligament stress vs. body mass index.

ANTHROPOMETRIC

Regression Analysis: UCL Operating Stress versus Total Arm Mass

Regression Equation

UCL Operating Stress = 8.97 + 0.87 Total Arm Mass

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	8.97	3.36	2.67	0.017	
Total Arm Mass	0.87	1.50	0.58	0.568	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.97998	2.08%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	3.014	3.014	0.34	0.568
Total Arm Mass	1	3.014	3.014	0.34	0.568
Error	16	142.084	8.880		
Lack-of-Fit	15	137.155	9.144	1.85	0.526
Pure Error	1	4.930	4.930		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.41	10.98	7.43	2.57 R	
7	11.15	11.81	-0.66	-0.27	X

R Large residual
X Unusual X

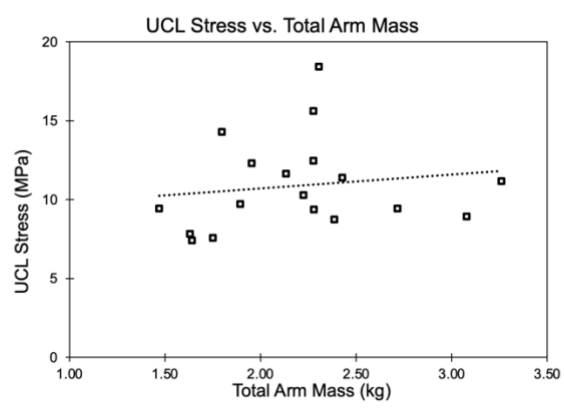


Figure B.4: Linear regression statistics and plot for ulnar collateral ligament stress vs. total arm mass.

ANTHROPOMETRIC

Regression Analysis: UCL Operating Stress versus Lower Arm Mass

Regression Equation

UCL Operating Stress = 7.42 + 4.07 Lower Arm Mass

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	7.42	4.09	1.81	0.088	
Lower Arm Mass	4.07	4.73	0.86	0.402	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.94396	4.43%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	6.428	6.428	0.74	0.402
Lower Arm Mass	1	6.428	6.428	0.74	0.402
Error	16	138.670	8.667		
Lack-of-Fit	14	90.894	6.492	0.27	0.948
Pure Error	2	47.776	23.888		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.41	11.12	7.29	2.56	R

R Large residual

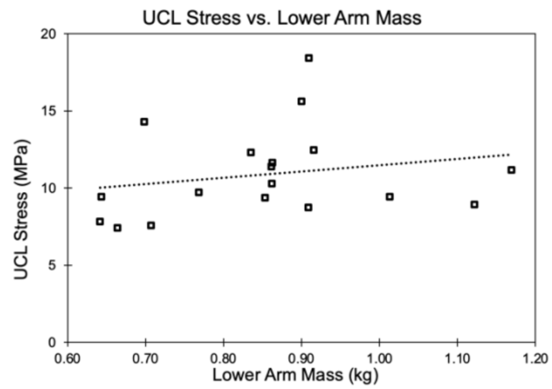


Figure B.5: Linear regression statistics and plot for ulnar collateral ligament stress vs. lower arm mass.

Regression Analysis: UCL Operating Stress versus Pitch Speed

Regression Equation

UCL Operating Stress = -15.15 + 0.456 Pitch Speed

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-15.15	8.37	-1.81	0.089	
Pitch Speed	0.456	0.146	3.12	0.007	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.37574	37.76%	33.87%	12.39%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	54.79	54.792	9.71	0.007
Pitch Speed	1	54.79	54.792	9.71	0.007
Error	16	90.31	5.644		
Total	17	145.10			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.41	15.40	3.01	1.67	X
14	15.60	9.23	6.37	2.83	R

R Large residual
X Unusual X

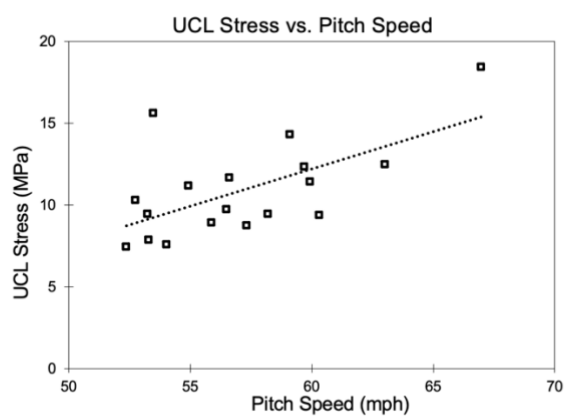


Figure B.6: Linear regression statistics and plot for ulnar collateral ligament stress vs. pitch speed.

Regression Analysis: UCL Operating Stress versus Max Shoulder ER

Regression Equation

UCL Operating Stress = 8.23 + 0.0169 Max Shoulder ER

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	8.23	3.89	2.12	0.050	
Max Shoulder ER	0.0169	0.0243	0.69	0.498	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.96707	2.92%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	4.242	4.242	0.48	0.498
Max Shoulder ER	1	4.242	4.242	0.48	0.498
Error	16	140.856	8.803		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid
1	18.41	10.86	7.55	2.62 R

R Large residual

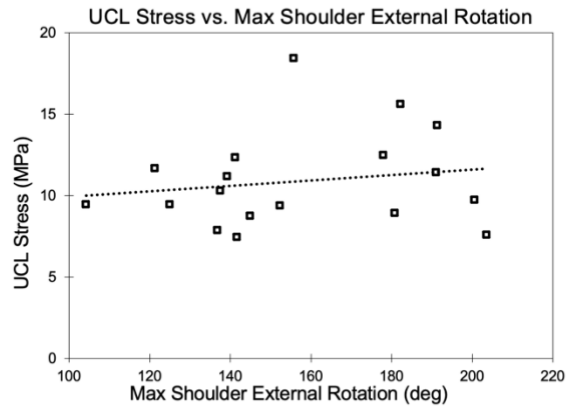


Figure B.7: Linear regression statistics and plot for ulnar collateral ligament stress vs. maximum shoulder external rotation.

Regression Analysis: UCL Operating Stress versus Elbow Flexion at MEVT

Regression Equation

UCL Operating Stress = 12.16 - 0.0160 Elbow Flexion at MEVT

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	12.16	3.01	4.04	0.001	
Elbow Flexion at MEVT	-0.0160	0.0369	-0.43	0.670	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.99388	1.16%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	1.685	1.685	0.19	0.670
Elbow Flexion at MEVT	1	1.685	1.685	0.19	0.670
Error	16	143.413	8.963		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid
1	18.41	10.99	7.42	2.56 R
14	15.60	10.31	5.29	2.04 R

R Large residual

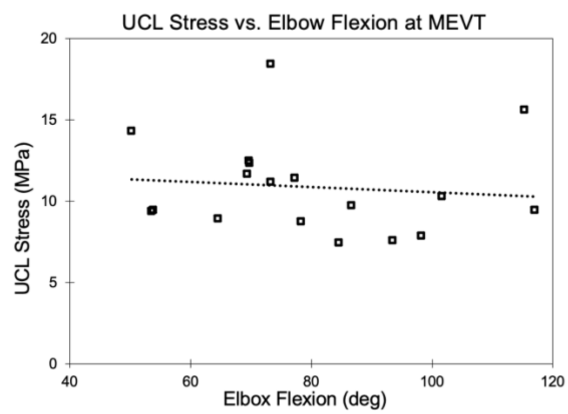


Figure B.8: Linear regression statistics and plot for ulnar collateral ligament stress vs. elbow flexion at maximum elbow varus torque.

Regression Analysis: UCL Operating Stress versus Elbow Flexion at BR

Regression Equation

UCL Operating Stress = 9.87 + 0.0359 Elbow Flexion at BR

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	9.87	1.87	5.28	0.000	
Elbow Flexion at BR	0.0359	0.0615	0.58	0.567	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.97982	2.09%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	3.029	3.029	0.34	0.567
Elbow Flexion at BR	1	3.029	3.029	0.34	0.567
Error	16	142.069	8.879		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid
1	18.41	11.68	6.73	2.63 R

R Large residual

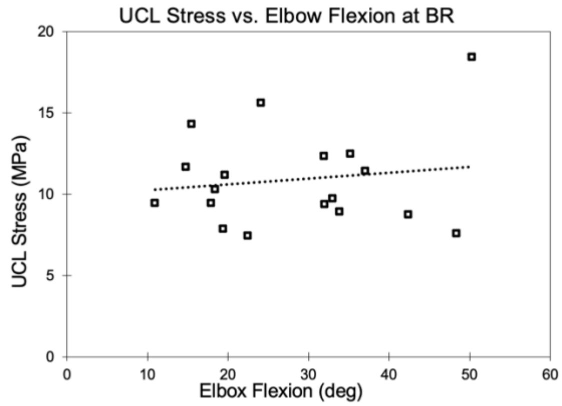


Figure B.9: Linear regression statistics and plot for ulnar collateral ligament stress vs. elbow flexion at ball release.

Regression Analysis: UCL Operating Stress versus Shoulder Abduction at FC

Regression Equation

UCL Operating Stress = 11.27 - 0.0046 Shoulder Abduction at FC

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	11.27	4.36	2.58	0.020	
Shoulder Abduction at FC	-0.0046	0.0518	-0.09	0.930	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.01067	0.05%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.071	0.07144	0.01	0.930
Shoulder Abduction at FC	1	0.071	0.07144	0.01	0.930
Error	16	145.027	9.06416		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid
1	18.41	10.95	7.46	2.63 R

R Large residual

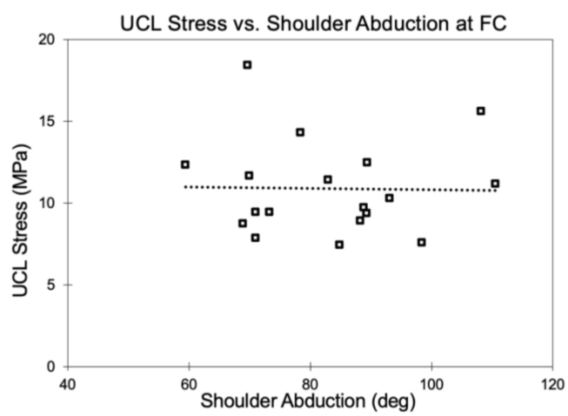


Figure B.10: Linear regression statistics and plot for ulnar collateral ligament stress vs. shoulder abduction at front foot contact.

Regression Analysis: UCL Operating Stress versus Max SERT

Regression Equation

UCL Operating Stress = 5.18 + 176.4 Max SERT

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	5.18	2.25	2.30	0.035	
Max SERT	176.4	67.2	2.62	0.018	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.51776	30.10%	25.73%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	43.67	43.672	6.89	0.018
Max SERT	1	43.67	43.672	6.89	0.018
Error	16	101.43	6.339		
Lack-of-Fit	14	87.49	6.250	0.90	0.645
Pure Error	2	13.93	6.966		
Total	17	145.10			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.410	13.419	4.991	2.22	R
2	9.360	14.037	-4.677	-2.19	R
14	15.600	10.033	5.567	2.30	R

R Large residual

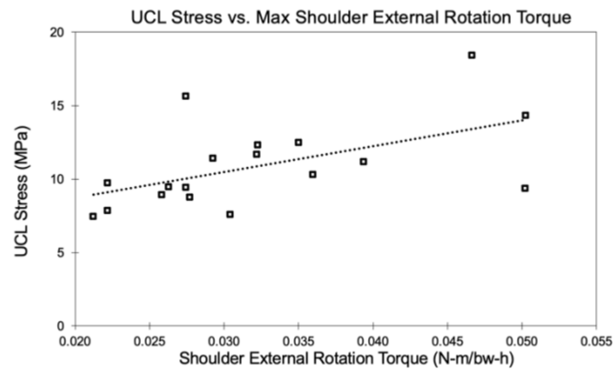


Figure B.11: Linear regression statistics and plot for ulnar collateral ligament stress vs. maximum shoulder external rotation torque.

PITCHING

Regression Analysis: UCL Operating Stress versus Maximum Elbow Varus Torque

Regression Equation

UCL Operating Stress = 1.83 + 412.2 Maximum Elbow Varus Torque

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.83	1.19	1.54	0.144	
Maximum Elbow Varus Torque	412.2	52.2	7.90	0.000	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.36088	79.58%	78.30%	73.42%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	115.47	115.466	62.35	0.000
Maximum Elbow Varus Torque	1	115.47	115.466	62.35	0.000
Error	16	29.63	1.852		
Total	17	145.10			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.410	17.330	1.080	1.04	X
7	11.150	8.344	2.806	2.19	R

R Large residual
X Unusual X

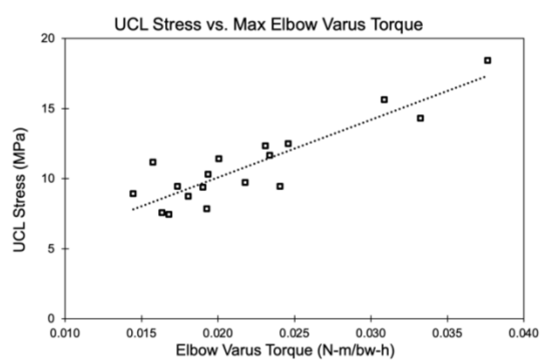


Figure B.12: Linear regression statistics and plot for ulnar collateral ligament stress vs. maximum elbow varus torque.

Regression Analysis: UCL Operating Stress versus Stride Length

Regression Equation

UCL Operating Stress = -0.2 + 0.134 Stride Length

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.2	12.2	-0.02	0.984	
Stride Length	0.134	0.146	0.92	0.374	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.93550	4.98%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	7.223	7.223	0.84	0.374
Stride Length	1	7.223	7.223	0.84	0.374
Error	16	137.875	8.617		
Lack-of-Fit	12	127.692	10.641	4.18	0.089
Pure Error	4	10.183	2.546		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.41	10.84	7.57	2.65	R

R Large residual

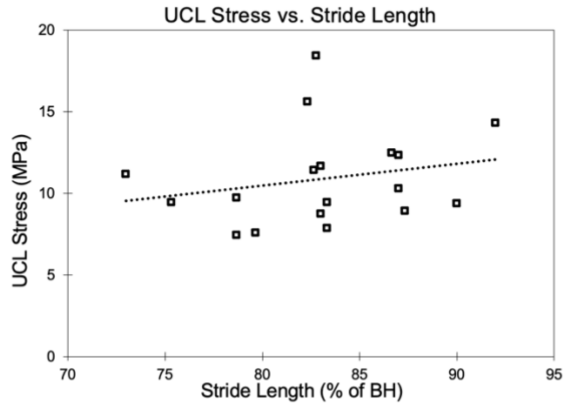


Figure B.13: Linear regression statistics and plot for ulnar collateral ligament stress vs. stride length.

Regression Analysis: UCL Operating Stress versus Front Foot Position

Regression Equation

UCL Operating Stress = 10.679 + 0.0397 Front Foot Position

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	10.679	0.765	13.96	0.000	
Front Foot Position	0.0397	0.0593	0.67	0.513	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.97012	2.72%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	3.952	3.952	0.45	0.513
Front Foot Position	1	3.952	3.952	0.45	0.513
Error	16	141.146	8.822		
Total	17	145.098			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid	
1	18.41	10.87	7.54	2.61	R
7	11.15	12.02	-0.87	-0.37	X

R Large residual
X Unusual X

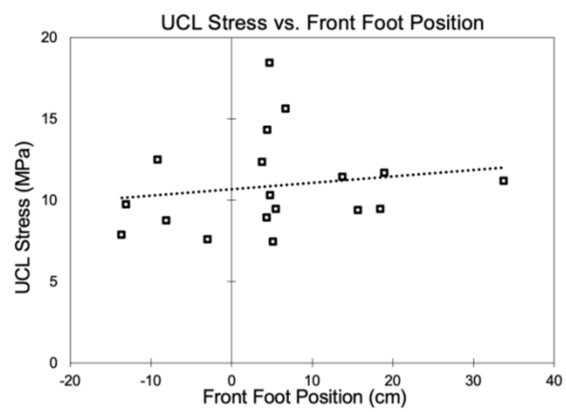


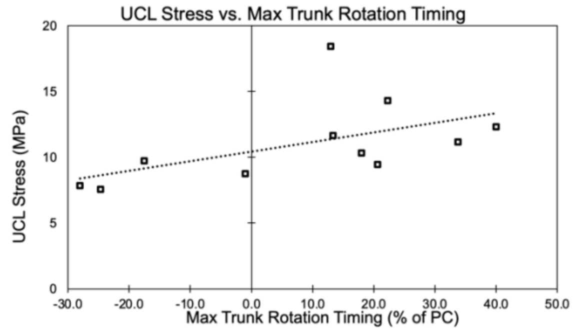
Figure B.14: Linear regression statistics and plot for ulnar collateral ligament stress vs. front foot position.

MAX TRUNK ROTATION TIMING

Regression Analysis: UCL Operating Stress versus Max Trunk Rotation Timing

Regression Equation

UCL Operating Stress = 10.439 + 0.0729 Max Trunk Rotation Timing



Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	10.439	0.906	11.52	0.000	
Max Trunk Rotation Timing	0.0729	0.0387	1.88	0.092	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.81635	28.29%	20.32%	7.91%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	28.16	28.160	3.55	0.092
Max Trunk Rotation Timing	1	28.16	28.160	3.55	0.092
Error	9	71.39	7.932		
Total	10	99.55			

Fits and Diagnostics for Unusual Observations

Obs	UCL Operating Stress	Fit	Resid	Std Resid
1	18.41	11.39	7.02	2.62 R

R Large residual

Figure B.15: Linear regression statistics and plot for ulnar collateral ligament stress vs. max trunk rotation timing.