ANALYSIS OF BASEBALL PITCHING: AN INVESTIGATION OF SHOULDER EXAM, BIOMECHANICS, AND INJURY

by

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ABSTRACT

HANNAH LEE STOKES. Analysis of Baseball Pitching: An Investigation of Shoulder Rotational Properties, Biomechanics, and Injury. (Under the direction of DR. NIGEL ZHENG)

Throwing arm injuries are common because of the demand on the shoulder. Shoulder exams and pitching mechanics are regularly monitored by team physicians. Excessive instability and joint loading in baseball pitching are risk factors for throwing arm injuries. Altering baseball pitching mechanics affects both performance and the risk of injury. There is limited work on the relationship between shoulder exams, baseball pitching biomechanics, and their relationship with injury. Knowledge of the relationship between shoulder exam variables, baseball pitching mechanics, and injuries may provide new insights for treatments and rehabilitation protocols and improve performance. The purpose of this study is to investigate the relationship among injuries, shoulder exam variables, and pitching biomechanics in collegiate baseball pitchers.

Pitching biomechanics, shoulder exam tests, and self-reported injury questionnaires from 177 collegiate baseball pitchers were used in this study. The study protocol was approved by an institutional board, and all participants gave written informed consent. Pitching motion data was collected at 240 Hz using a motion capture system. A custom program was used to calculate all kinematic and kinetic variables of baseball pitching. The shoulder range of motion and flexibility were quantitatively recorded using a custom-made wireless device. Self-reported injury questionnaires were filled out during testing and during yearly follow-ups. All subjects with injuries were divided into three groups: injury history, follow-up injury, and both injury history and follow-up injury. All pitchers were healthy at the time of testing. Analysis of variance with Tukey post-hoc tests, Pearson correlation tests, and multinomial logistic regression tests were performed using SPSS to compare differences among shoulder exam, pitching biomechanics, and injury questionnaire variables with alpha set to 0.05.

When comparing shoulder exam variables to pitching biomechanics there were 34 positive and 21 negative significant correlations (positive R: 0.230 to 0.356 and negative R: -0.203 to -0.245, respectively). When comparing shoulder exam variables to injuries there was a significant difference in the dominant internal shoulder rotational flexibility among the three injury groups (p=0.026). There was a significant difference in the shoulder horizontal adduction angle among the three injury groups (p=0.045). A throwing biomechanics index was created finding fifteen significant pitching biomechanics variables related to injury. The throwing biomechanics index found significant relationships with the pitcher's height (p=0.017), mass (p=0.000), age (p=0.010), forearm length (p=0.000), shoulder flexibility (p=0.002), and shoulder range of motion (p=0.010).

Our findings show that the shoulder exam, pitching biomechanics, and injury questionnaire variables are related. Optimizing pitching mechanics and shoulder flexibility reduces injury and improve performance. Pitching mechanics consists of kinematics and kinetics and improvement is found when pitching with proper mechanics. Shoulder flexibility is improved by proper strengthening and conditioning. The throwing biomechanics index's relationship with both demographics and the shoulder exam shows that the single index is representative and can lead to new insights. The ability to understand the relationship between shoulder exam variables, baseball pitching mechanics (motions and joint loadings), and injuries helps further our knowledge and

pushes forward the underlying goal of this study which is to improve performance and reduce injuries.

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DEDICATION

To those who have gone before me

To those who walk with me

To those who will go after me

Remember we are better together

Challenge yourself to learn and play everyday

Love with all your heart, soul, strength, mind, and being

Practiced gratitude will unlock endless joy

Always live on fire

“Play is the highest form of research.” – Albert Einstein

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LIST OF ABBREVIATIONS

AA	Abduction/Adduction
ANOVA	Analysis of Variance
AP	Anterior/Posterior
BMI	Body Mass Index
EF	Extension/Flexion
EPA	End Point Angle
ER	External Rotation
GIRD	Glenohumeral Internal Rotation Deficit
HAA	Horizontal Abduction/Adduction
IE	Internal/External
IR	Internal Rotation
ML	Medial/Lateral
ROA	Resistant Onset Angle
ROM	Range of Motion
PD	Proximal/Distal
SI	Superior/Inferior
SLAP	Superior Labrum Anterior Posterior
SRF	Shoulder Rotational Flexibility
TRMD	Total Rotational Motion Deficit
UCL	Ulnar Collateral Ligament
VV	Varus/Valgus

CHAPTER 1: INTRODUCTION

The introduction chapter covers the motivation, scope of the project, objectives, research hypotheses, and organization of content. This chapter serves to create an understanding of the backbone of the project so that as this thesis builds it fulfills all that is laid out here. Let us now begin the journey of the analysis of baseball pitching with an investigation of shoulder exam, biomechanics, and injury.

1.1. Motivation

The motivation of this study is to reduce injury and improve performance. In sport, throwing-arm injuries are common because of the high and repetitive stresses, primarily to the throwing arm. These injuries keep athletes from playing and can be career ending. This not only hurts the athlete but their team, family, and even fans. Injuries are prevalent in athletes of all ages. USA baseball reports that there are annually more than 15.6 million amateur players in ballparks and playgrounds around the country (*About USA Baseball*, 2022). In the Major League Baseball system (including both Major and Minor League affiliates) there are on average 8,250 players annually employed (Cooper, 2018). This includes tee-ball, little league, middle and high school, and collegiate, and professional baseball players (Figure 1). Baseball pitching is very demanding on the shoulder; the shoulder internally rotates at about 7,000 degrees per second and the force applied is greater than 800 Newtons (Zheng et al., 2004; Zheng et al., 1999). On average, across youth, college, and the professional level, 30% of players report having a throwing arm injury, annually (Boltz et al., 2021; A Popchak et al., 2015;

QD, 2019). This is a significant amount, which prompts the goal to further understand the mechanism throwing arm injuries (shoulder and elbow) to enhance preventative protocols, improve performance, and promote better rehabilitation practices. This work extends beyond baseball to other sports and all shoulder and elbow injuries.

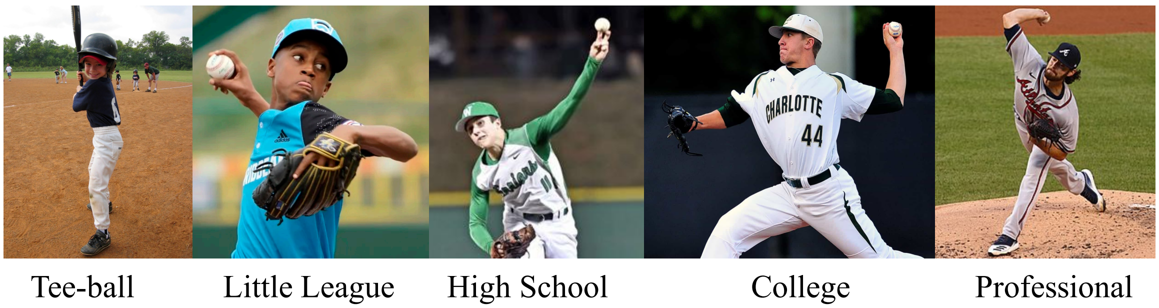

Figure 1: Baseball is played at all ages from tee-ball to the professional level.

1.2. Scope of Project

The scope of this project begins with bringing collegiate (both division I and II) baseball pitchers into the lab for testing. The testing contains three main pillars the shoulder exam, the pitching biomechanics, and the injury questionnaire (Figure 2). The shoulder exam was where the athletes lay on their backs and their shoulder range of motion, flexibility, and stiffness were measured. The pitching mechanics was where high speed cameras recorded the athlete pitching. This allowed us to capture both the athletes' body position and calculate joint loadings. Finally, the injury questionnaire was where the athletes reported if they have had any injuries or surgeries within the past year. The goal in investigating these three components was to give a big picture perspective in hopes to gain understanding of how to reduce injury and improve performance.

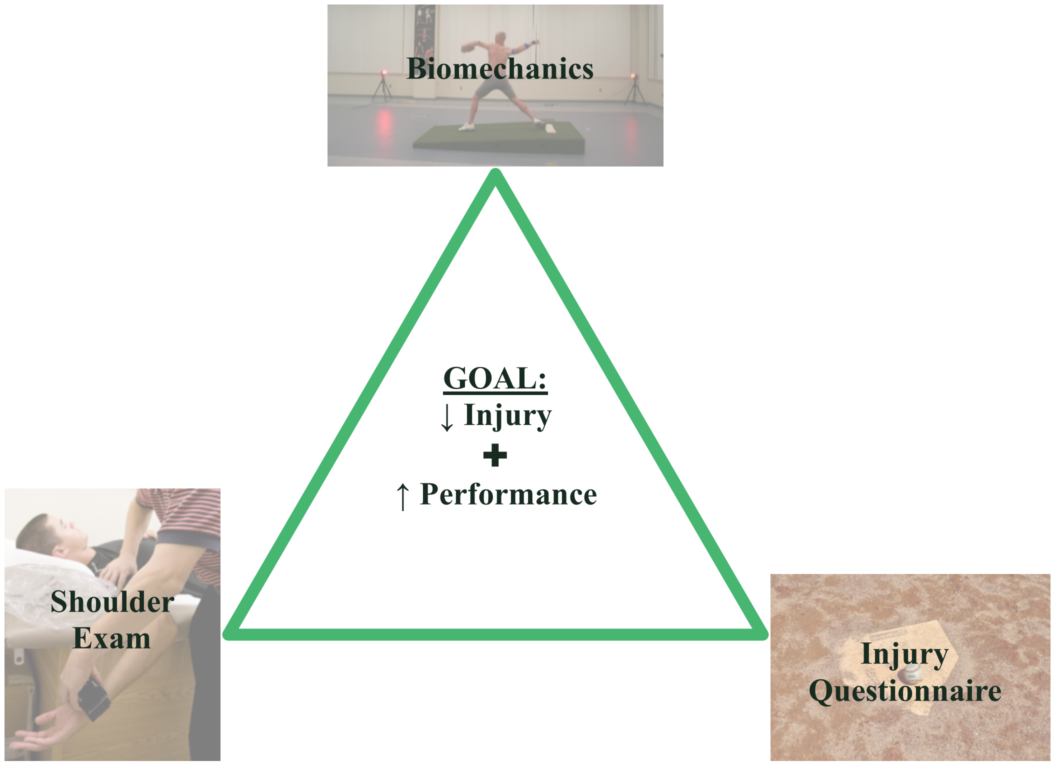

Figure 2: The goal of the project was to ultimately reduce injury and increase performance with scope focusing on three pillars of the shoulder exam, biomechanics, and injury questionnaire.

1.3. Objectives

The objectives of this study dive into the investigation of the scope of this project following the triangle diagram (Figure 2). There are five primary objectives that will be explored throughout this thesis all in collegiate baseball pitchers. The first objective is the investigation of the demographics of the study with the shoulder exam, baseball pitching biomechanics, and throwing arm injury variables. The second objective is the investigation of the shoulder exam and baseball pitching biomechanics variables. The third objective is the investigation of throwing arm injury and the shoulder exam variables. The fourth objective is the investigation of baseball pitching biomechanics and throwing arm injury variables. The fifth, and final, objective is the investigation of the relationship of the shoulder exam, baseball pitching biomechanics, and throwing arm injury by introducing a throwing biomechanics index.

1.4. Research Hypotheses

This experiment assumed null hypotheses for all five objectives, presented above. The first hypothesis is there will be no relationship between the demographics of the study with the shoulder exam, baseball pitching biomechanics, and throwing arm injury variables. The second hypothesis is there will be no relationship between the shoulder exam and baseball pitching biomechanics variables. The third hypothesis is there will be no relationship between throwing arm injury and the shoulder exam variables. The fourth hypothesis is there will be no relationship between baseball pitching biomechanics and throwing arm injury variables. The fifth, and final, hypothesis is there is no relationship between the shoulder exam, baseball pitching biomechanics, and throwing arm injury in comparison to the throwing biomechanics index.

1.5. Organization of Content

Chapter 1 provides an overview of the purpose and goals of this research study. Chapter 2 gives the background of anatomy, baseball, and common injuries. Chapter 3 is a literature review that provides relevant information on the shoulder exam in baseball pitchers, biomechanics of baseball, and prevalence of injury. Chapter 4 details the methods used to complete this research including the recruitment of pitchers, shoulder exam, experimental motion capture set up to capture the biomechanics of baseball pitching, injury questionnaires, regression modeling, and statistical analysis procedures. Chapter 5 presents the results of the research. Chapter 6 discusses the results of this study with other relevant work and goes over limitations and future recommendations. Finally, Chapter 7 summarizes the work and presents the conclusions.

CHAPTER 2: BACKGROUND

The background chapter covers the functional anatomy of the elbow and shoulder, motions of the shoulder and elbow, baseball pitching basics, and common throwing arm injuries. This chapter serves to give the elementary background of all that will be discussed and focused on in this thesis. This chapter is foundational for the chapters to come.

2.1. Functional Anatomy of Shoulder and Elbow

The functional anatomy of baseball pitching includes understanding the form and the function of the body. Anatomy direction terms and body planes are important and common methods of identifying and clearly communicating body structures (Figure 3). The three main planes of the body are the transverse, frontal/coronal, and sagittal/lateral plane (Weineck, 1986). The transverse plane divides the body into top and bottom. The frontal/coronal plane divides the body into front and back. The sagittal/lateral plane divides the body into right and left.

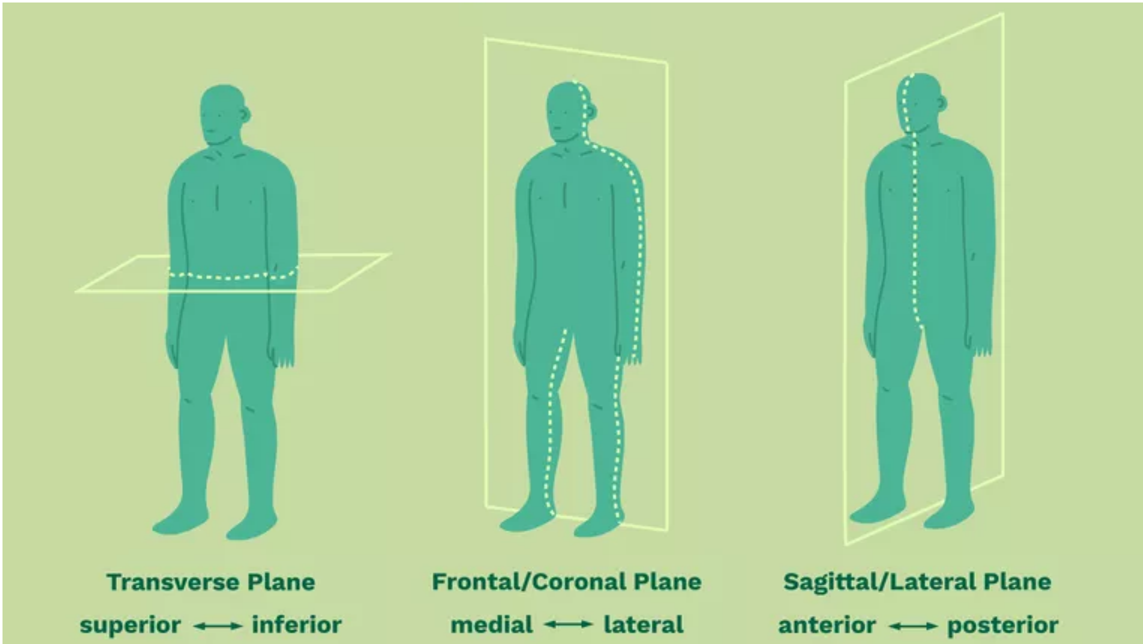

Figure 3: The three planes of the body with directional terms defined (Image from ThoughtCo (Bailey, 2019)).

Further, there are more direction terms that help define the location of body structures. Superior describes something that is above, and inferior describes something that is below. The most superior part of the human body is the head and the most inferior is the feet. Medial describes something close to the midline, and lateral describes something to the sides (away from the midline). When thinking of the arms and the torso, the arms are lateral, and the torso is medial. Anterior describes something that is front, and posterior describes something that is back. When thinking of the patella (kneecap) and the scapula (shoulder blade), the patella is anterior, and the scapula is posterior.

The discussion of baseball pitching narrows our focus to the throwing arm, looking at both the shoulder and the elbow (Figure 4). The shoulder is comprised of three bones: the humerus (upper arm), the scapula (shoulder blade), and the clavicle (collarbone). The elbow is comprised of three bones: the humerus (upper arm), the ulna (forearm), and the radius (forearm).

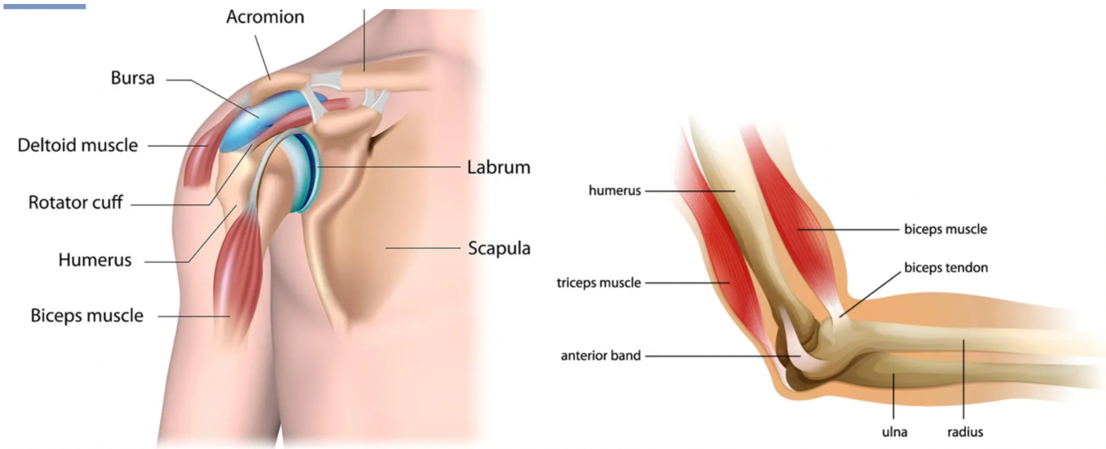

Figure 4: Anatomy of shoulder and elbow showing the bones, muscles, and other soft tissues surrounding the joint (Image from Orthopaedic Specialists (Noorani, 2019)).

Joints are where two or bones meet. While the shoulder is often referred to as a single joint, it is technically made up of four joints. This allows for the complex motions we see present in the shoulder. The four joints are: the sternoclavicular, acromioclavicular, glenohumeral, and scapulothoracic joints (Di Giacomo et al., 2008). The two most known and susceptible to injuries are the glenohumeral and the acromioclavicular joint. The glenohumeral joint is the main joint in the shoulder and is where the top of the humerus nestles into the socket of the scapula. This ball and socket joint allows for the large circular motion of the arm. The acromioclavicular joint is where the clavicle meets the acromion (which is located on the top of the scapula). This gliding synovial joint mainly helps facilitate raising the arm over the head.

The other two shoulder joints that are less well known and less likely to be injured are the sternoclavicular and scapulothoracic joint. The sternoclavicular joint is where the clavicle meets the sternum (breastbone). The gliding synovial joint helps facilitate several shoulder movements, including shrugging, extending the arm behind the body, and moving the shoulder forward and backwards. The scapulothoracic joint is not a true joint but it is where the scapula meets and glides across the posterior thoracic rib cage.

The elbow is a synovial hinge joint that joins the humerus in the upper arm and the radius and the ulna in the forearm (Hoshika et al., 2019). Further, the bones give rise to three joints. The humeroulnar, humeroradial, and proximal radioulnar joint. Humeroulnar joint is the joint between the trochlea on the medial aspect of the distal end of the humerus and the trochlear notch on the proximal ulna. The humeroulnar hinge joint is responsible for flexion and extension. Humeroradial joint is the joint between the capitulum on the lateral aspect of the distal end of the humerus with the head of the radius. The humeroradial joint is where the radius and humerus articulate. It is partly responsible for pronation and supination. The proximal radioulnar joint is between the peripheral edge of the radial head articulates with the radial notch of the ulna. The proximal radioulnar joint is a trochoid joint responsible for pronation or supination of the forearm. The humeroulnar and the humeroradial joints are the joints that give the elbow the characteristic hinge like properties.

The intrinsic muscles of the shoulder are also known as the scapulohumeral muscular group, are deeper muscles which originate from the scapula or the clavicle and insert on the humerus are the rotator cuff. The rotator cuff is comprised of the following four muscles: supraspinatus, infraspinatus, teres minor, and subscapularis. The most frequently injured group of muscles and tendons within the shoulder is the rotator cuff. All four muscles connect the scapula and the humerus. They are essential players in almost every type of shoulder movement. Balanced strength and flexibility in each of the four muscles are vital to maintain the functioning of the entire shoulder. The rotator cuff as a group provides strength and stability to the shoulder, by keeping the humeral head inside of the glenoid fossa (scapula).

The extrinsic muscles of the shoulder are larger, more superficial, and they originate on the thorax and attach to the bones of the shoulder complex, which include: the latissimus dorsi, teres major, pectoralis major, and pectoralis minor. The elbow has two main muscles groups the primary elbow flexors and the primary elbow extensors. The primary elbow flexors include the brachialis, biceps brachii, and brachioradialis. The primary elbow extensors include the triceps and anconeus.

The shoulder labrum is another one of the most frequently injured parts of the shoulder (Figure 4). The labrum is a slippery, tough ring of cartilage that rims the glenoid cavity. The purpose of the labrum is to keep the humerus in place and ensure smooth movement of the ball and socket joint.

Ligaments connect bones to bones. A network of ligaments stabilizes the shoulder and includes the glenohumeral, coracohumeral, and transverse humeral ligaments. The glenohumeral ligaments are three ligaments that reinforce the front of the shoulder's glenohumeral joint. The coracohumeral ligament is a strong and broad band that strengthens the upper aspect of the bicep brachii. The transverse humeral ligament which attaches to two different points at the top of the humerus and creates a tunnel for the bicep tendon to pass under. There is a collection of ligaments that connect the bones forming the elbow joint to each other, contributing to the stability of the joint. The humeroulnar and the humeroradial joints each have a ligament connecting the two bones involved in the articulation: the ulnar collateral and the radial collateral ligaments. The ulnar collateral ligament is composed of three parts: an anterior, posterior, and inferior band. The radial collateral ligaments have a distal blend called the annular ligament and a proximal blend called the quadrate ligament.

The last soft tissue to speak of is the bursa. A bursa is a fluid-filled sac that counters friction at a joint. Bursae are located at various points around the body where muscles, tendons, and ligaments rub against bone during movement. The two primary bursae of the shoulder are the subscapular bursa and the subacromial bursa. The subscapular bursa is located between the glenohumeral joint and the subscapularis muscles. The subacromial bursa is located directly under the acromion (bony projection of scapula) that helps the rotator cuff motion. The elbow bursa is a thin sac of fluid that lies between the boney tip of the elbow and the back of the arm (the olecranon) and the skin.

2.2. Motions of the Shoulder and Elbow

The major motions of the shoulder are abduction and adduction, flexion and extension, internal and external rotation, and horizontal abduction and adduction and of the elbow are flexion and extension (Figure 5). Shoulder abduction is upward lateral motion of the humerus away from the body and adduction is downward medial motion of the humerus toward the body. Shoulder flexion is anterior motion of the humerus and extension is posterior motion of the humerus. Shoulder internal rotation is the motion of the humerus medially around its long axis toward the midline and external rotation is the motion of the humerus laterally around its long axis away from the midline. Shoulder horizontal abduction is the motion of the humerus in the transverse plane away from the chest and horizontal adduction is the motion of the humerus in the transverse plane toward and across the chest. Elbow flexion of the forearm at the elbow joint involves decreasing the angle between the forearm and the arm at the elbow joint. Elbow extension involves increasing the angle between the arm and forearm.

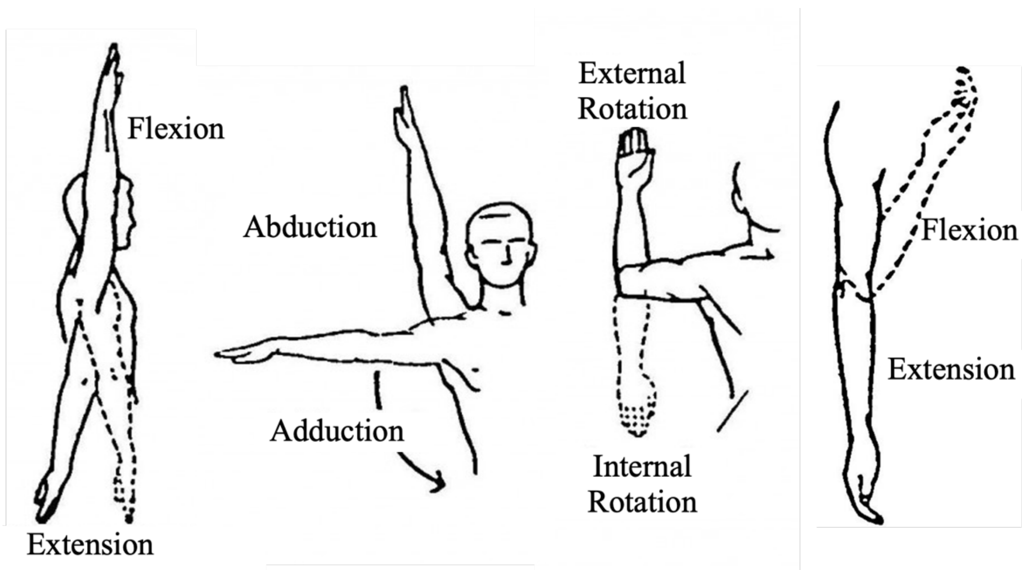

Figure 5: The most common motions of the shoulder (left three) and the elbow (right one).

The healthy range of motions of these motions follow with all the measurements are taken from the anatomical position where the athlete is standing upright and facing forward with each arm hanging on either side of the body unless further specified. The quantifiable range of motion for shoulder abduction is one hundred and eighty to one hundred and eighty-five degrees. The quantifiable range of motion for shoulder adduction is seventy-five degrees. The quantifiable range of motion for shoulder flexion is one hundred and eighty to one hundred and ninety degrees. The quantifiable range of motion for shoulder extension is forty to sixty degrees. The quantifiable range of motion for shoulder horizontal adduction is one hundred and thirty-five degrees. The quantifiable range of motion for shoulder horizontal abduction is forty-five degrees. These measurements are taken with the athlete standing upright and facing forward with each arm abducted ninety degrees. The quantifiable range of motion for shoulder internal rotation is seventy to ninety degrees. The quantifiable range of motion for shoulder external rotation is seventy to ninety degrees. These measurements are taken in two positions. First, from the anatomical position with the elbow flexed ninety degrees and secondly, with the athlete is standing upright and facing forward with each arm abducted ninety degrees and the elbow flexed ninety degrees. The quantifiable range of motion for elbow flexion is one hundred and fifty degrees. The quantifiable range of motion for elbow extension is zero degrees.

2.3. Baseball Pitching Basics

Overhead baseball pitching motion is often divided into six phases: wind up, stride, arm cocking, arm acceleration, arm deceleration, and follow through (Figure 6) (Dillman et al., 1993; Fleisig et al., 1995; Werner et al., 1993). The wind-up phase has components of balance and initial forward movement while the stride encompasses arm path, foot contact, stride length, stride angle, arm position at foot contact and the relationship of speed and timing between the lead leg hips and throwing arm. The arm cocking phase incorporates elbow position in flexion, shoulder external rotation and trunk inclination. The arm acceleration includes shoulder internal rotation velocity, trunk forward movement towards home base, and body position at ball release. The arm deceleration and follow through include trunk positioning, lead leg extension, and dissipation of force through upper extremity horizontal adduction.

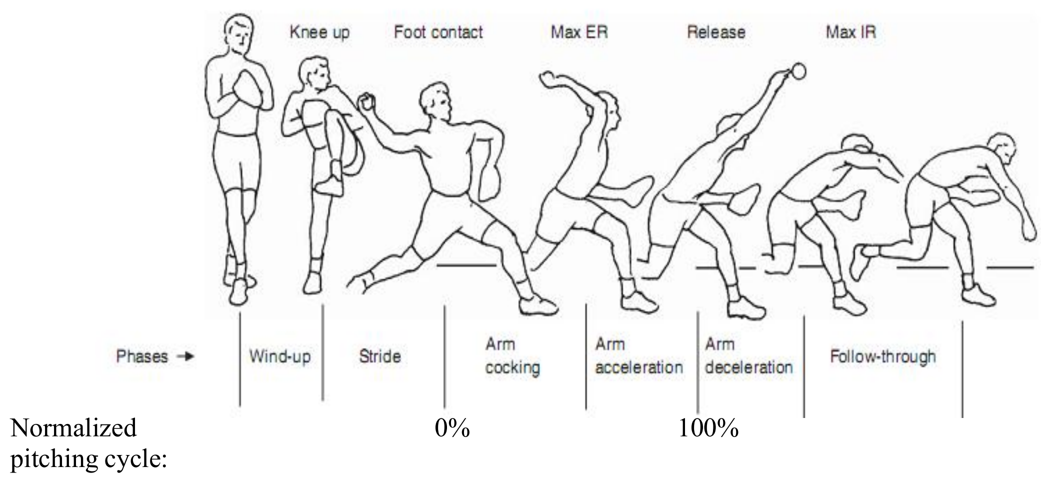

Figure 6: Baseball pitching phases with the normalized time of 0% being foot contact and 100% being ball release, where ER: external rotation and IR: internal rotation.

To compare timing, kinematic, and kinetic variables it is common to normalize the pitching cycle. The variables are normalized from the foot contact (0%) to ball release (100%) as labeled above (Figure 6). The windup and stride phase varies in style and timing, and data from -50% to 0% were included for analysis. The arm deceleration and follow through similarly varies in style and timing based off the pitch and mechanics, and data from 100% to 200% were included for analysis. This normalization is helpful in comparing varying pitches from one pitcher and between different pitchers.

2.4. Common Throwing Arm Injuries

Overhead throwing places extremely high stresses on the shoulder, especially anatomy that keeps the shoulder stable. In throwing athletes, these high stresses are repeated many times and can lead to overuse injuries (George S. Athwal et al., 2021). Outside of baseball other common sports with throwing arm injuries include volleyball, tennis, swimming, football, and some track and field events.

The arm cocking, arm acceleration, and arm deceleration phases place the greatest strain on the throwing arm. During the early arm cocking phase, there is a rapid movement of the torso rotating which causes the arm to lag the upper torso and forces the throwing shoulder into horizontal abduction, which causes an increase in the shoulder anterior force and shoulder horizontal abduction moment (Manzi et al., 2022). All the stress is on the anterior capsule, posterior rotator cuff, and labrum. The most common injuries to occur during the early arm cocking phase are anterior instability and posterior impingement. Shoulder impingement is when the tendons of the rotator cuff get pinched in the bones of the shoulder. This injury can cause swelling, irritation, and pain. Shoulder impingements are most seen in individuals who are involved in sports and other activities with a lot of overhead rotational motion. Impingements are called when the tendon is torn or swollen, the bursa is irritated and inflamed, or from abrasions from bone spurs.

During the late arm cocking phase, the forearm lags behind the arm and forces the arm into shoulder external rotation, which causes an increase in the shoulder external rotation moment and elbow valgus moment. The maximum external rotation angle helps put speed on the ball, but also forces the head of the humerus forward. From the shoulder external rotation moment, it stresses the superior labrum and the posterior rotator cuff and labrum. From the elbow valgus moment, it stresses the ulnar nerve, ulnar collateral ligament (UCL), radial head, and olecranon. The most common injuries are superior labrum anterior-posterior (SLAP) lesion, posterior and subacromial impingement, UCL sprain, medial epicondylitis, and stress fracture (Altchek & Dines, 1995).

The late arm cocking phase is where there is the highest risk for injury in throwing athletes. Further, is a deeper dive in the most common injuries. A SLAP lesion or tear is a cartilage tear that is located around the rim of the shoulder joint (Burkhart & Morgan, 2001). With this injury there will be pain reaching overhead and the shoulder will seem weak. It may feel like the shoulder joint is catching, locking, popping, or grinding. The two most common causes are after you do repetitive motions or if you fall and your shoulder absorbs a lot of force. An UCL sprain is a tear to one of the ligaments on the inner side of your elbow. An UCL sprain can occur suddenly (acute) or can gradually come on over time with wear and tear. Medial epicondylitis is characterized by pain from the elbow to the wrist on the inside (medial side) of the elbow. The pain is caused by damage to the tendons that bend the wrist toward the palm. The shoulder stress fracture is where a bone breaks and cracks of either the clavicle, humerus, or the scapula. The most common breaks are clavicle and humerus. The most common causes for this injury are falling from height, contact sports, or other traumatic events.

During the acceleration phase, there is a rapid shoulder internal rotation and elbow extension, which causes an increase in shoulder and elbow distraction forces. From the increase in forces, it stresses the biceps tendon, rotator cuff, joint capsule, and UCL. The most common injuries are biceps tendonitis, rotator cuff strain, medial epicondylitis, and UCL sprain. Tendinitis is inflammation or irritation of a tendon and is most located in rotator cuffs and/or biceps tendon. The rotator cuff tear is the injury where one of the four rotator cuff muscles and tendons tear. There are two different types of tears a partial and a full thickness tear. There are two main causes an acute tear which can be caused by falling on an outstretched arm or lifting something too heavy and a degenerative tear which can be caused by repetitive stress, lack of blood supply, and bone spurs. With this injury it is common for the shoulder to hurt at night and when lifting things.

During the deceleration phase, there is a deceleration of the shoulder rotation, which causes and increase in the shoulder distraction forces and shoulder horizontal adduction moment. The ligaments and rotator cuff tendons at the back of the shoulder absorb significant stress to decelerate the arm and control the humeral head (Davidson et al., 1995). From the increase of forces and torques, it stresses the biceps tendon, superior labrum, posterior rotator cuff, and joint capsule. The most common injuries are biceps tendonitis, SLAP lesion, rotator cuff strain, and subacromial impingement.

Overall, throwing athletes can have a wide range of throwing arm injuries because of the complexity, high stress, and repetitive movement. When one structure becomes weakened or injured due to repetitive stress, other structures in the throwing arm must handle the overload. The most vulnerable structures in the shoulder are the rotator cuff and labrum and in the elbow is the UCL. The injury mechanism is closely related to the motion and loading during the baseball pitch.

CHAPTER 3: RELEVANT LITERATURE REVIEW

The literature review chapter covers the shoulder exam of baseball pitchers, biomechanics of baseball pitchers, and throwing arm injuries in baseball pitchers. This chapter serves to present and elaborate on all the current literature that is relevant to this thesis work. This chapter provides a clear picture on what has been done in the field and will show the novel and contributing work of this thesis.

3.1. Shoulder Exam of Baseball Pitchers

Shoulder ROM is often examined by team physicians, but shoulder flexibility and stiffness are not well quantified. To mitigate and monitor the common risk of injury team clinicians commonly perform shoulder physical exams for baseball pitchers at all levels throughout the season. During physical exams, the shoulder is examined looking at positioning, dysfunction, range of motion, and many other signs displaying shoulder health condition (Cotter et al., 2018; Greenberg et al., 2017; Stokes et al., 2021). Previous studies have monitored the elbow and shoulder range of motion, flexibility, and many other properties (Laudner et al., 2012; Laudner et al., 2021; Stokes et al., 2021; Yasui et al., 2012).

The most common and well-established variables are glenohumeral internal rotation deficit (GIRD) and total rotational motion deficit (TRMD). GIRD is defined as a bilateral deficit (throwing versus nonthrowing arm) of 20° or greater (Burkhart et al., 2003a, 2003b, 2003c). TRMD is defined as a bilateral deficit (throwing versus nonthrowing arm) of 5° or greater (Wilk et al., 2002). Further, pathological GIRD is defined when pitchers have both GIRD and TRMD (Rose & Noonan, 2018). The presence of pathological GIRD is thought to be a better determination of risk for future injury than anatomical GIRD alone (Manske et al., 2013).

Shoulder physical exams outcomes have been related to injuries, but very rarely looked at with baseball pitching biomechanics. A previous study showed that higher shoulder external rotation may be advantageous because it lowers the force and torque on the shoulder joint (Stokes et al., 2021). Laudner et al recently investigated the glenohumeral horizontal adduction motion (during the physical exam) to shoulder and elbow forces in collegiate baseball pitchers; finding there were statistically significant bilateral differences and pitchers with -10º or less of horizontal adduction range of motion (ROM) had statistically significantly higher shoulder abduction, horizonal abduction torque, elbow flexion, and valgus torque during pitching (Laudner et al., 2021). This motivates the purpose of this study to investigate the relationship of shoulder exam variables with baseball pitching biomechanics.

The monitoring of shoulder health and its relationship with injury is well documented; however, there are limitations. In a previous study, Wilk et al found that pitchers with TRMD had a higher risk for injury with injury and the increased the risk of elbow injury by 2.6 times (Wilk et al., 2014). In a further study, Wilk et al found that GIRD, TRMD, and flexion deficit were not statistically significantly related to shoulder injuries or surgeries (Wilk et al., 2015). In a study that investigated in cricket and bowlers and badminton players showed that the presence of GIRD does not always lead to injury or loss of playing time (Bathia et al., 2017). The presence of GIRD is quite common, and more investigations are needed to determine the impact it has on injury mechanisms. One limitation of the GIRD and TRMD is the requirement of the non-throwing arm, depending on the non-throwing arm's mobility it would greatly bias the measurement. There is a relationship between shoulder physical exam and throwing arm injuries and these results provide motivation for this study. The relationship between shoulder physical exams and throwing arm injuries has been studied, but the connections are still not clear.

3.2. Biomechanics of Baseball Pitching

The ability to identify the ideal pitching mechanics is beneficial to the sport. Thompson et al found that increasing both shoulder rotation angle and shoulder angular velocity has shown to increase ball speed and performance in youth baseball pitching (Thompson et al., 2018). Further, a previous study showed that the increase in ball speed and shoulder external rotation angle was related to increased shoulder range of motion (Seroyer et al., 2010). There are many factors that affect pitching mechanics and all need to be monitored to improve understanding. The importance of understanding the ideal mechanics at all ages is just as important whether it is youth or professional pitchers. Proper pitching mechanics is imperative to keeping pitchers healthy and improving performance.

Many studies have explored baseball pitching mechanics and performance. Laudner et al found that pitchers with -10° or less of horizontal adduction range of motion in their throwing shoulder create statistically significantly more shoulder abduction and horizontal abduction torque, as well as more elbow flexion and valgus torque, during the pitching motion (Laudner et al., 2021). Another study, found that exploiting centrifugal force for throwing arm acceleration is a key factor in achieving proper throwing mechanics that increases the ball speed and reduces the shoulder joint loading (Naito et al., 2019). Many factors influence the proper mechanics.

Many studies explore the biomechanics and performance of all age groups. A study on elite youth baseball pitchers examining their pitching mechanics showed that during the highest torque arose during the arm-cocking phase that overtime could cause deformation and even damage based off the magnitude and location (Sabick et al., 2005). Werner et al explored the biomechanics of the elbow during baseball pitching motivated after doing cadaver studies and they found four main functions of the elbow during pitching, which include: forearm muscles help UCL generate varus torque during arm cocking, increase of triceps and decrease of biceps activity increases elbow extension angular velocity, large elbow flexion torque occurs in the deceleration phase, and all muscles contract during ball release which causes a large force on the elbow (Werner et al., 1993). Many studies explore how the throwing arm acts and responds during the pitching motion all to try to find the best mechanics.

Baseball pitching is a complex movement that puts a lot of stress on the throwing arm (both the elbow and shoulder). Injury history affects performance when athletes return to sport, potentially caused by the altered shoulder external rotational properties, which may in turn alter the shoulder joint loading. A previous study found that higher shoulder joint loading (forces and torques) in competitive baseball players leads to more injury incidences (Oyama, 2012). Further, in a study analyzing pitching mechanics, emphasized that poor pitching mechanics could compound the repetitive stress placed on the soft tissues of the shoulder and elbow and had been implicated as a potential risk of injury (Calabrese, 2013). It is well understood that high joint loading with repetitive motions can lead to potential injury. Again, showing the importance of understanding of the optimal position of the throwing-arm during baseball pitching is critical in improving performance and reducing injuries.

3.3. Throwing Arm Injuries in Baseball Pitchers

Overhead throwing places extremely high stresses on the shoulder, especially on the anatomical structures that keep the shoulder stable. In baseball pitchers, these high stresses are repeated many times that can lead to overuse injuries. During baseball pitching, the greatest risk or injury is in the late cocking and deceleration phase because there are greatest forces and torques on the shoulder (Oyama, 2012; Seroyer et al., 2010; Zheng et al., 1999). During the late cocking phase, the maximum external rotation angle helps put speed on the ball but also put significant stress on the front of the shoulder that with many repetitions can loosen the joint anteriorly. During the deceleration and follow-through phase the ligaments and rotator cuff tendons on the back of the shoulder absorb energy under high stress that can lead to overuse injuries. The most vulnerable structures for the shoulder are the rotator cuff and the labrum and for the elbow is the ulnar collateral ligament (Burkhart et al., 2003b; Coughlin et al., 2019; Hodgins et al., 2018; Zheng, 2003). Monitoring throwing shoulder and preventing these injuries is advantageous for athletes, coaching, and clinicians.

There is a high prevalence of baseball injuries at all levels. First, diving into the collegiate level, the focus of this study, a study showed the injury rate was consistently higher in competition than it was in practice with the preseason generally higher than regular season but there is some fluctuation (Boltz et al., 2021). Most of the injuries are attributed to noncontact and overuse injuries. Another review on college baseball pitchers, further emphasize the importance of proper preseason conditioning in order to reduce the injury rate throughout the season (Dick et al., 2007). At the professional level, elbow injuries are the most common to require surgery with damage on the medial UCL (Ciccotti et al., 2017). Another common injury in both the minor and major leagues is forearm flexor injuries with the most common being the flexor strain (Hodgins et al., 2018). Ultimately, this prevalence is taking the players out of the game which is harmful to the players careers and in some cases even sidelines them for good. There is great importance in further understanding the injury mechanisms to help combat the frequency of injuries.

An injury, even after healing, may affect shoulder stiffness, flexibility, and ROM. Limited shoulder external rotational properties may lead to injuries in baseball pitchers. Increased shoulder looseness or excessive flexibility has led to instabilities and increased injury incidences (Laudner et al., 2012). The top 3 throwing arm injuries are rotator cuff injuries, ulnar collateral ligament injuries of the elbow, and medial epicondylitis (Gesicki, 2019). Throwing activity causes adaptive changes to shoulder ROM and humeral retrotorsion (Greenberg et al., 2017; Oyama et al., 2013). Shoulder external rotational properties are not well quantified, leaving incomplete understanding of the injury mechanisms during baseball pitching.

Injuries and pain are major causes for why baseball pitchers are on the injured list at all levels. Pitching requires such high and repetitive demands on the body that the osseous adaptation that allows greater external rotation and less internal rotation of the shoulder (Crockett et al., 2002). The change bony structures and range of motion results from playing years of baseball from tee-ball, little league, middle and high school, and collegiate, and professional baseball players. Overuse and fatigue are other factors that could cause injury. Ultimately there are many factors that influence the incidence of injury, including the following: joint loading, flexibility, experience of pitcher, and pitching mechanics (A Popchak et al., 2015; Zheng & Barrentine, 2000). The connection between injury and shoulder joint loading is not clear, leaving a knowledge gap and motivation for this study.

CHAPTER 4: METHODOLOGY

The methodology chapter covers the recruiting pitchers, shoulder exam, biomechanics of baseball pitching, injury questionnaire, regression modelling, and statistical analysis. This chapter serves to thoroughly explain the processes of this thesis in completion although data were collected previously and retrieved from the lab databank for this dissertation. All data was retrieved from a data bank with IRB approval (Appendix A). The chapter provides the story from the beginning of all that this thesis includes.

4.1. Recruiting Pitchers

For this study, data from 177 National Collegiate Athletic Association (NCAA) baseball pitchers: Division I (n=117) and Division II (n=60) (mean ± standard deviation: age, 20 ± 1 years; height, 186 ± 7 cm; mass, 85 ± 9 kg) were retrieved from the lab databank (Appendix A). These pitchers were used because they performed all three tasks of the shoulder exam, the injury questionnaire, and the biomechanics testing. The NCAA baseball teams were recruited using recruitment letters (Appendix B). The study protocol for this study was approved by an institutional review board at the University of North Carolina at Charlotte, and all pitchers gave written informed consent (Appendix C). All pitchers were healthy at the time of testing, or they were excluded from the study.

4.2. Shoulder Exam

A custom wireless device was developed for testing purposes and this methodology has been previously published (Stokes et al., 2021; Zheng & Eaton, 2012a). It utilizes a force sensor and an orientation sensor that is powered by a rechargeable 9-volt battery (Zheng & Eaton, 2012b). The sensor was calibrated and validated showing it to be reliable and has high repeatability. It transmits the force applied and the forearm orientation to the host computer for real-time display (Figure 7). The accuracy of the force measurement is less than 1 Newton and the accuracy of angle measurement is less than 1.5 degrees due to the limitation of the 7 bit wireless transmitter.

Figure 7: The shoulder exam where the shoulder and arm are supported, and the custom wireless device records the internal rotation and external rotation range of motions (Image modified from previous publication (Stokes et al., 2021; Zheng & Eaton, 2012a)).

The arm orientation and force applied during testing were recorded at 100 Hz using a Bluetooth wireless connection. Audio feedback was set when the applied force reached 40 N. Both the applied force and forearm orientation were displayed in real-time on a computer screen. The device's repeatability was evaluated by testing repeatedly on 12 healthy male subjects between 24 and 48 hours after their signed consents were obtained. The Cronbach's Alpha (α) was used to determine the internal consistence reliability. The standard error of measurement (SEM) was calculated from the standard deviation (S) and the square root of (1-α), i.e. $SEM = \frac{S}{\sqrt{1-\alpha}}$. The minimal detectable change with 90% confidence was calculated from MDC90 = SEM*1.65*1.414. Both external and internal rotations were tested for both throwing and non-throwing arm.

From the repeatability study, the mean ± standard deviation of Cronbach's Alpha values for ROA, and EPA were 0.946±0.035 and 0.974±0.015 respectively, which indicates a good reliability of tests. SEMs were 2.1 and 1.8 degrees for resistant onset angle (ROA) and end point angle (EP), respectively. The minimal detectable changes (MDC) with 90% confidence were 5.0 and 4.1 degrees for ROA and EPA, respectively.

Twenty trials were collected from each subject: ten trials for both the throwing and non-throwing arm including 5 trials on external rotation and 5 trials on internal rotation. A 15 second pause was taken between trials. ROA, EPA, and shoulder rotational flexibility (SRF) were calculated for both arms and both rotational directions from recorded data (Figure 8). ROA was defined when the applied force was 2 N. EPA was defined when the applied force was 40 N. SRF was defined by the angle rotated by one-unit rotational torque (Nm) after combining the force moments of the force applied at the wrist and gravitational force of the arm relative to the rotational axis (longitudinal axis of the upper arm). For each shoulder rotational properties variable (internal ROA, internal EPA, internal SRF, external ROA, external EPA, external SRF) averages from 5 trials were used. Shoulder rotational properties of both arms were recorded. Both the internal and external EPA, SRF, and ROA groups were designated as follows: low (< mean – 1 SD), medium (mean ± 1 SD), and high (> mean + 1 SD) for comparison purposes.

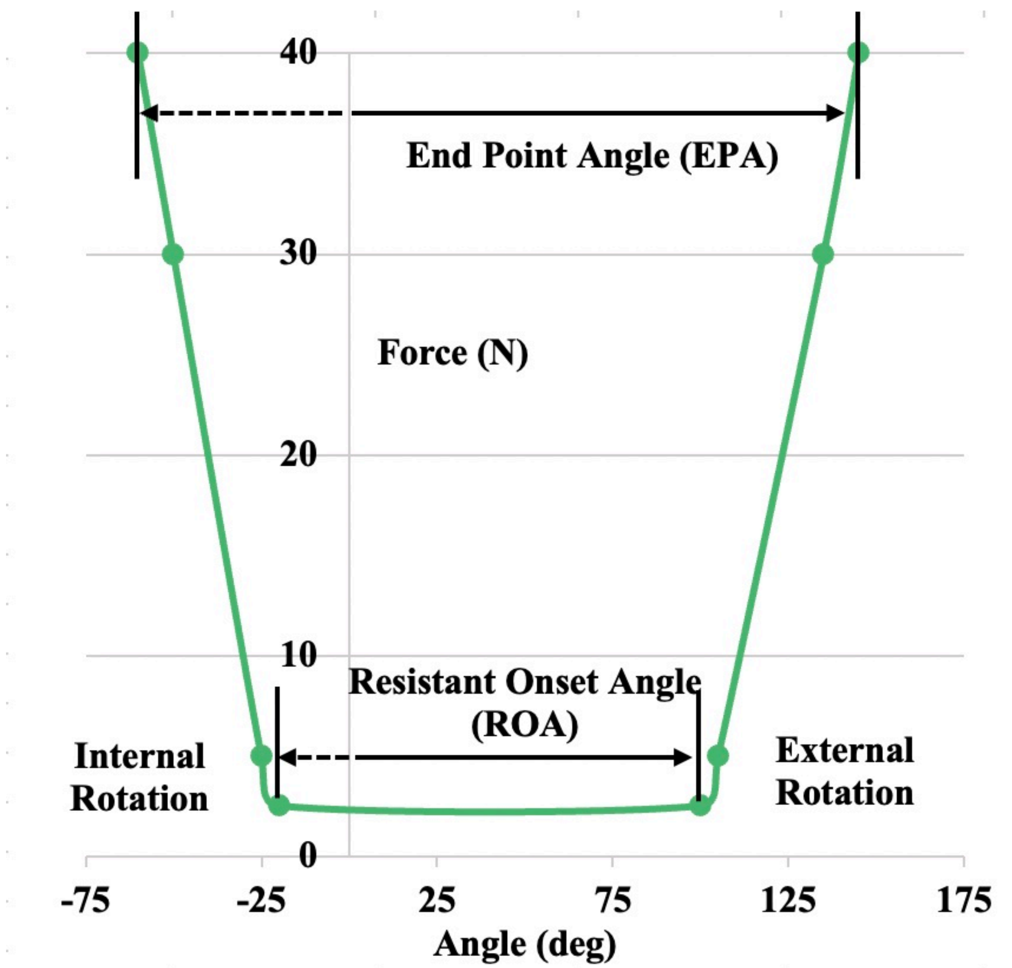

Figure 8: The output of the shoulder exam that defines the variables of interest, where the solid line represents the external variables, and the dotted line represents the internal variables (Image modified from previous publication (Stokes et al., 2021; Zheng & Eaton, 2012a)).

Further variables as discussed include total ROM, GIRD, TRMD, and shoulder external rotation over internal rotation ratio (SEIR). The total ROM is the external EPA plus the internal EPA. The bilateral difference of total rotation is defined as the total rotation of the throwing arm minus the total rotation of the non-throwing arm, where TRMD is any value less than -5 degrees (Equation 1). The bilateral difference of internal rotation is defined as internal EPA of the throwing arm minus the internal EPA of the non-throwing arm, where GIRD is any value less than -20 degrees (Equation 2). SEIR is defined as the external EPA divided by the internal EPA of the throwing arm (Equation 3).

$$Bilateral\ difference\ of\ total\ ROM = dominant\ arm\ total\ ROM - nondominant\ arm\ total\ ROM \qquad \text{(Equation 1)}$$

$$Bilateral\ difference\ of\ internal\ rotation = dominant\ arm\ internal\ rotation - nondominant\ arm\ internal\ rotation \qquad \text{(Equation 2)}$$

$$SEIR = \frac{External\ EPA}{Internal\ EPA} \qquad \text{(Equation 3)}$$

The values of SEIR vary with the external rotation and internal rotation variables (Figure 9). All three pitchers have the same total range of motion but based on the breakdown of the external rotation and internal rotation they have different SEIR values. These three pitchers are not the only way these SEIR values can be achieved, but they are examples of different arm angles. The center pitcher has the average external rotation, internal rotation, and SEIR for this study. The variations in the shoulder physical exam variables of all pitchers directs influences the throwing arm motion and joint loading during baseball pitching.

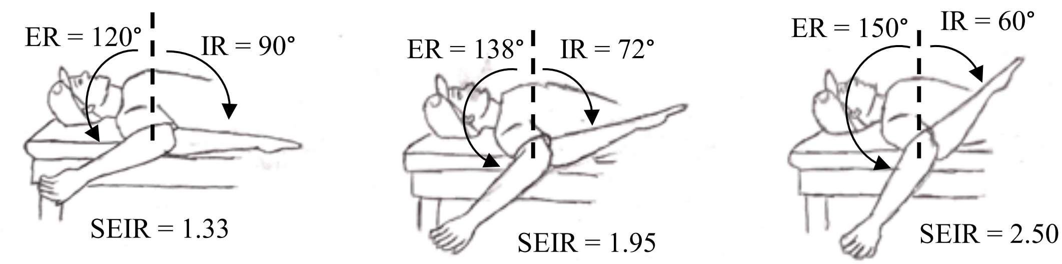

Figure 9: The relationship between the external rotation (ER) and internal rotation (IR) greatly impacts the SEIR. All pitchers in this figure have the same total range of motion (210º) with varying SEIR values (from left to right: low, study average, and high).

4.3. Biomechanics of Baseball Pitching

The biomechanics of baseball pitching section thoroughly explains into the experimental set up, motion data analysis, and kinematics and kinetics. This section breaks down all the processes to be able to collect data through outputting all biomechanics variables. This deeply dives into all the details needed to collect all the data for the second pillar of this study.

4.3.1. Experimental Set Up

Overall, we have collected pitching mechanics from 177 pitchers. Motion data were collected at 240 Hz using our 10-camera motion capture system (VICON MX-F40, UK). The system was calibrated for the area of interest. Seventeen passive reflective markers were attached to major joints for biomechanical analysis (Figure 10). These markers were attached bilaterally to the distal end of the midtoe, lateral malleolus, lateral femoral epicondyle, greater trochanter, lateral tip of the acromion, and lateral humeral epicondyle on both sides. Additionally, on the throwing arm, two reflective markers were placed medially and laterally on the wrist and 1 on the back side of the distal end of the middle metacarpal. The human musculoskeletal system is broken down into a series of jointed segments that are approximated as rigid bodies. These markers compose each segment, and the cameras can uniquely track the location and the orientation of the bodies in space. This knowledge of the location and orientation allows the six motions (three translations and three rotations) to be calculated for two adjacent jointed segments.

Figure 10: Reflective markers attached to major joints for biomechanical analysis of baseball pitching.

Pitchers were allowed to warm up by stretching and throwing. The experimental set up shows the testing views of A: T-pose, used as the reference frame, B: reflective markers on a pitcher, C: the portable mound with the pitcher in action, and D: the strike zone that the pitchers were throwing to (Figure 11). The pitchers threw balls from an artificial portable mound that was 60 feet 6 inches from home base. Gun speeds were measured by sports using radar gun. Ten fastball pitches were then collected. Ball speed and location in the strike zone were recorded for each pitch. Three best strike pitches were analyzed, and their average was used to represent the pitcher's pitching motion.

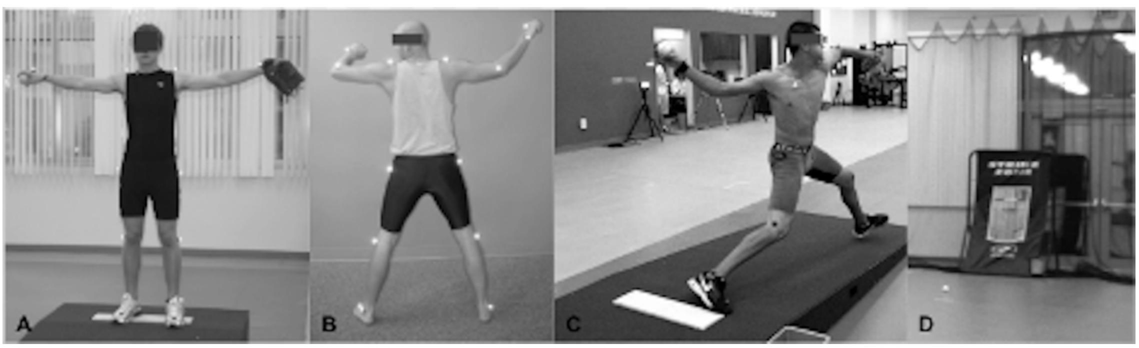

Figure 11: Experimental setup with the various testing views: A) T-pose, B) reflective markers, C) portable mound with pitcher in action, and D) strike zone (Image from previous publication (Stokes et al., 2021)).

4.3.2. Motion Data Analysis

Manual digitization is the process of extracting coordinates from the images recorded on the cameras. The digitizing allows the connections of the markers to form the jointed segments so that the whole body is represented by the series of small markers.

This data was then exported from the Vicon system to then be loaded into custom program for analysis. The custom program was developed in MATLAB.

During data collection there are several potential sources of error or noise. The most could be from optoelectrical devices, calibration processes, or human error during digitizing. It is essential for the raw data to be filtered and smoothed. The position data is digitally filtered with a Butterworth low-pass filter with a cutoff frequency of 20 Hz. Further the data are then passed through the filter a second time in reverse order to eliminate phase distortion.

The whole pitching motion was divided into six phases: wind-up, strike, arm cocking, arm acceleration, arm deceleration and follow-through (Figure 12). The end of the strike phase, i.e., the lead foot contact (FC) was aligned at 0% and used for normalization. The end of arm acceleration, i.e., the ball release (BR) was used for normalization and labeled as 100%. Data from -50% to 200% was recorded from wind-up to follow-through was analyzed. The clean and complete data was then ready for further analysis.

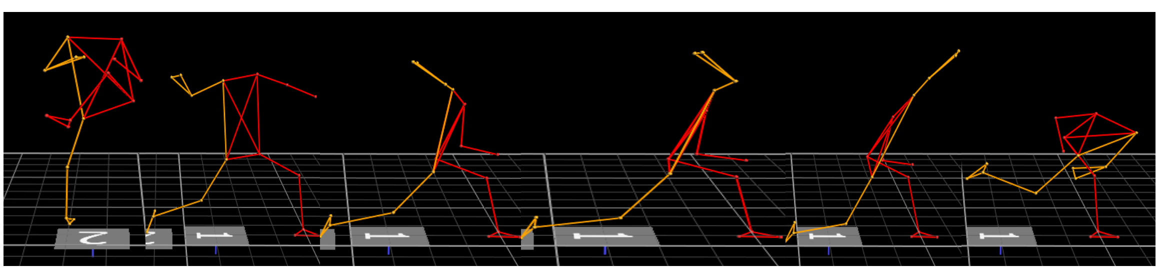

Figure 12: The digitized output of the six baseball pitching phases (wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow through).

4.3.3. Kinematics and Kinetics

Kinematics is the study of motion of mechanical points, bodies, and systems without consideration of their associated physical properties and the forces acting on them. In calculating the kinematic variables, the first step is to define the reference system. The process of calculating the reference system was adapted from the methodology previously presented (Zheng et al., 2004). The global reference system is defined as the Z, being the vertical axis, the X, being the horizontal axis perpendicular to Z in the direction of pitching, and the Y, being the horizontal axis perpendicular to X direction (parallel to the theoretical first to third base line). This is called the global reference system because it is relative to the space in the lab or on the baseball field. The local reference system is defined for each body segment, which follows similarly the convention of the global system of the Z, vertical, the X, horizontal in the direction of pitching, and the Y, horizontal perpendicular to X. The local X axis is defined by the vectors of the leading and throwing shoulder (Equation 4). The local Y axis is determined by the trunk vector and the local X axis (Equation 5 and 7). The local Z axis is determined by the local X axis and Y axis (Equation 6).

The local coordinate system of the shoulder is defined as:

$$\text{X axis: } \vec{I}_{sx} = \frac{\vec{V}_{sh-t} - \vec{V}_{sh-l}}{|\vec{V}_{sh-t} - \vec{V}_{sh-l}|} \qquad \text{(Equation 4)}$$

$$\text{Y axis: } \vec{I}_{sy} = \frac{\vec{I}_{trunk} \times \vec{I}_{sx}}{|\vec{I}_{trunk} \times \vec{I}_{sx}|} \qquad \text{(Equation 5)}$$

$$\text{Z axis: } \vec{I}_{sz} = \vec{I}_{sx} \times \vec{I}_{sy} \quad \text{(Equation 6)}$$

$$\vec{I}_{trunk} = \frac{\vec{V}_{sh-t} + \vec{V}_{sh-l} - \vec{V}_{hip-t} - \vec{V}_{hip-l}}{|\vec{V}_{sh-t} + \vec{V}_{sh-l} - \vec{V}_{hip-t} - \vec{V}_{hip-l}|} \quad \text{(Equation 7)}$$

where $\vec{V}_{sh-t}$ is the throwing shoulder vector, $\vec{V}_{sh-l}$ is the lead shoulder vector, $\vec{V}_{hip-t}$ is the throwing side hip, and $\vec{V}_{hip-l}$ is the lead side hip in the global coordinate system. If $\vec{V}_{el-t}$ is the throwing elbow vector and $\vec{V}_{w-t}$ is the throwing wrist vector, then $\vec{V}_{ua-t} = \vec{V}_{el-t} - \vec{V}_{sh-t}$ is the throwing upper arm vector and $\vec{V}_{fa-t} = \vec{V}_{w-t} - \vec{V}_{el-t}$ is the throwing forearm vector.

The process of calculating the kinematics was adapted from the methodology previously presented (Zheng et al., 2004). The motion of the throwing shoulder are shoulder abduction, shoulder external rotation, and shoulder horizontal abduction (Figure 13). The shoulder angles including shoulder abduction (Equation 8), shoulder horizontal abduction (Equation 9), and shoulder external rotation (Equation 10) can be defined by:

Shoulder abduction:

$$\alpha = 180 - cos^{-1}\left(\frac{\vec{V}_{ua-t} \cdot \vec{I}_{sz}}{|\vec{V}_{ua-t}|}\right) \quad \text{(Equation 8)}$$

Shoulder horizontal abduction:

$$\beta = \begin{cases} tan^{-1}\left(\frac{\vec{V}_{ua-t} \cdot \vec{I}_{sy}}{\vec{V}_{ua-t} \cdot \vec{I}_{sx}}\right) & right - handed \\ -tan^{-1}\left(\frac{\vec{V}_{ua-t} \cdot \vec{I}_{sy}}{\vec{V}_{ua-t} \cdot \vec{I}_{sx}}\right) & left - handed \end{cases} \quad \text{(Equation 9)}$$

Shoulder external rotation:

$$\gamma = \begin{cases} tan^{-1}\left(\frac{\vec{V}_{fa-t}\cdot\vec{I}_{uaz}}{\vec{V}_{fa-t}\cdot\vec{I}_{uay}}\right) & right-handed \\ 180 - tan^{-1}\left(\frac{\vec{V}_{fa-t}\cdot\vec{I}_{uaz}}{\vec{V}_{fa-t}\cdot\vec{I}_{uay}}\right) & left-handed \end{cases} \quad \text{(Equation 10)}$$

where $\vec{I}_{uay} = \frac{\vec{I}_{trunk} \times \vec{V}_{ua-t}}{|\vec{V}_{ua-t}|}$ and $\vec{I}_{uay} = \frac{\vec{V}_{ua-t} \times \vec{I}_{uay}}{|\vec{V}_{ua-t}|}$.

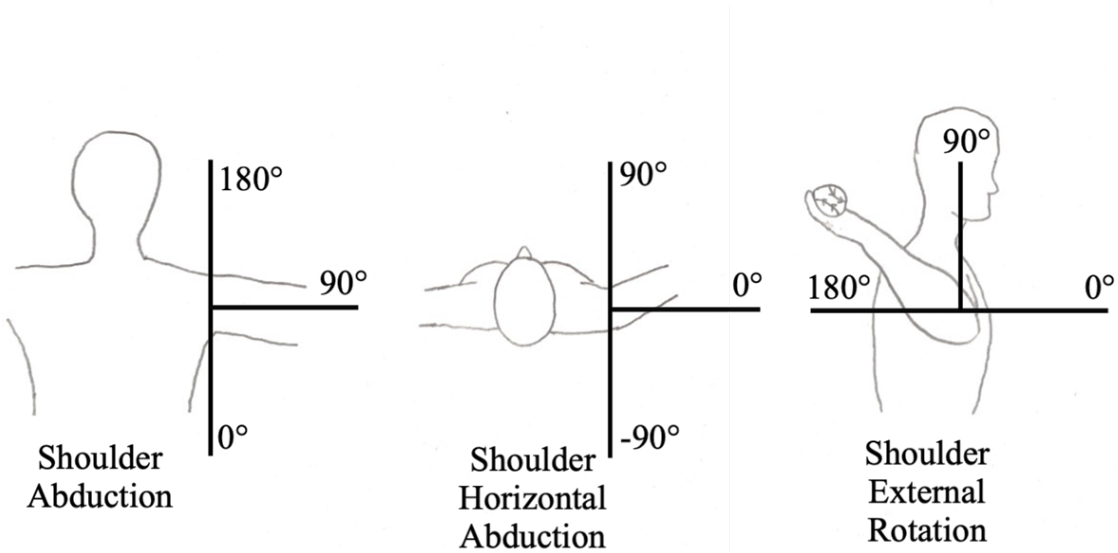

Figure 13: Shoulder (right shoulder in this figure) motion definitions and ranges of the throwing arm.

The elbow is made of three joints from the connections of upper arm (humerus) and forearm (radius and ulna) and connected with collateral ligaments to form the joint capsule. The humeroulnar joint is considered the primary joint which allows the elbow to hinge. The largest movement of the elbow is flexion and extension (Figure 14). The elbow flexion angle (Equation 11) is determined by the upper and forearm vectors and can be defined by:

Elbow flexion:

$$\theta = cos^{-1}\left(\frac{\vec{V}_{ua-t}\cdot\vec{V}_{fa-t}}{|\vec{V}_{ua-t}|\cdot|\vec{V}_{fa-t}|}\right) \qquad \text{(Equation 11)}$$

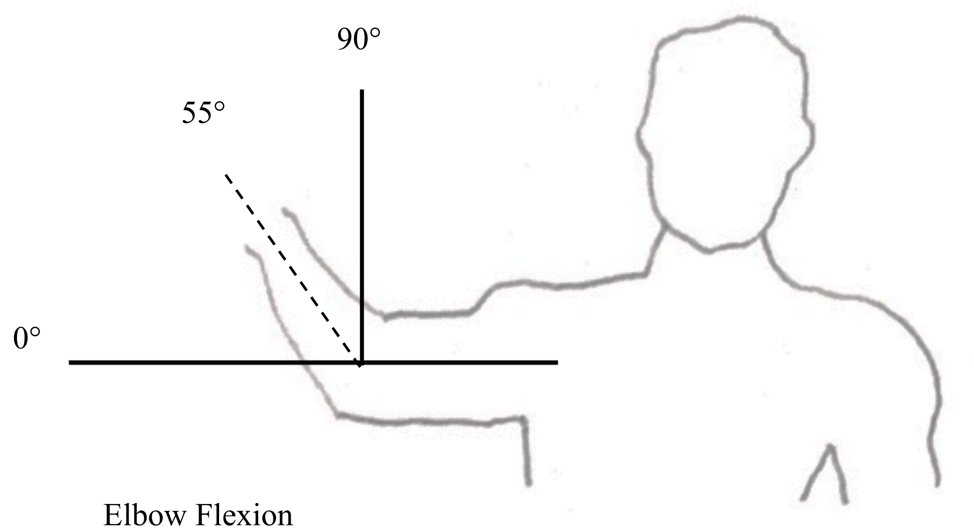

Figure 14: Elbow (right elbow in this figure) motion definitions and ranges of the throwing arm.

Other angles relevant to baseball pitching motion are the trunk and spine movements. The trunk motion is described relative to the global coordinate system and has two primary movements the trunk forward (Equation 12) and side (Equation 13) tilt angles. The trunk forward and side tilt angles can be defined by:

Trunk forward tilt:

$$\xi = tan^{-1}\left(\frac{\vec{I}_{trunk}\cdot\vec{I}_{gx}}{\vec{I}_{trunk}\cdot\vec{I}_{gz}}\right) \qquad \text{(Equation 12)}$$

Trunk side tilt:

$$\zeta = \begin{cases} tan^{-1}\left(\frac{\vec{I}_{trunk}\cdot\vec{I}_{gy}}{\vec{I}_{trunk}\cdot\vec{I}_{gz}}\right) & right-handed \\ -tan^{-1}\left(\frac{\vec{I}_{trunk}\cdot\vec{I}_{gy}}{\vec{I}_{trunk}\cdot\vec{I}_{gz}}\right) & left-handed \end{cases} \qquad \text{(Equation 13)}$$

Further the spine movements are not analyzed by vertebrae but by instead defined as a whole. The markers on the hip and shoulders allow the spine motion to be calculated. A local coordinate system is defined at the pelvis (p) with $\vec{I}_{px}$ pointing from the leading hip to the throwing side hip (Equation 14). The local y axis is defined by the trunk vector and the local x axis (Equation 15). The local z axis is determined by the local x axis and y axis (Equation 16). The local system's three axes are defined by:

$$\vec{I}_{px} = \frac{\vec{V}_{hip-t} - \vec{V}_{hip-l}}{|\vec{V}_{hip-t} - \vec{V}_{hip-l}|} \qquad \text{(Equation 14)}$$

$$\vec{I}_{py} = \vec{I}_{trunk} \times \vec{I}_{px} \qquad \text{(Equation 15)}$$

$$\vec{I}_{pz} = \vec{I}_{px} \times \vec{I}_{py} \qquad \text{(Equation 16)}$$

The two motions of the spine that can be defined are the spine lateral bending and the spine axial rotation. To determine these angles the local coordinate system of the shoulder and the local coordinate system of the pelvis are used. The spine lateral bending (Equation 17) and axial rotation (Equation 18) angles can be defined by:

Spine lateral bending:

$$\delta = tan^{-1}\left(\frac{\vec{I}_{sx}\cdot\vec{I}_{pz}}{\vec{I}_{sx}\cdot\vec{I}_{px}}\right) \qquad \text{(Equation 17)}$$

Spine axial rotation:

$$\omega = \begin{cases} tan^{-1}\left(\frac{\vec{I}_{sx}\cdot\vec{I}_{py}}{\vec{I}_{sx}\cdot\vec{I}_{px}}\right) & right-handed \\ -tan^{-1}\left(\frac{\vec{I}_{sx}\cdot\vec{I}_{py}}{\vec{I}_{sx}\cdot\vec{I}_{px}}\right) & left-handed \end{cases} \qquad \text{(Equation 18)}$$

The angles of the major joints of interest during baseball pitching were defined and these angles are the relative motion of one body segment to another. The body is constructed by a chain of segments that are all connected and impacting one another. The final step for kinematics is calculating the linear and angular velocities and accelerations. Velocity is the change of position over time and acceleration is the change of velocity over time. The camera sampling frequency was 240 Hertz, so each time step was 0.004 seconds. To minimize error a five-point derivative was used to calculate both velocity and acceleration. The velocity and acceleration of location x at time frame i is calculated using two points before (i-1, i-2) and two points after (i+1, i+2) of the position or velocity data, respectively. Where f is the sample frequency, the velocity (Equation 19) and acceleration (Equation 20) can be defined by:

Velocity:

$$\vec{v}_x[i] = \frac{1}{12}(-\vec{p}_x[i+2] + 8 * \vec{p}_x[i+1] - 8 * \vec{p}_x[i-1] + \vec{p}_x[i-2]) * f \qquad \text{(Equation 19)}$$

Acceleration:

$$\vec{a}_x[i] = \frac{1}{12}(-\vec{v}_x[i+2] + 8 * \vec{v}_x[i+1] - 8 * \vec{v}_x[i-1] + \vec{v}_x[i-2]) * f \qquad \text{(Equation 20)}$$

Kinetics is the study of forces and moments acting on mechanical points, bodies, and systems. In baseball pitching we are most interested in the forces and moments on the throwing arm or the shoulder and elbow. To calculate the forces and torques the following is needed: body movements, anthropometric data, and external forces. The body movements include all that was discussed previously, the positions, velocities, and accelerations. The anthropometric data includes the mass of each body segment, moment of inertial, and location of the mass center. The external forces include the ball’s resistive force, the ground reaction force, and the gravitational force. The process of calculating the kinetics was adapted from the methodology previously presented (Zheng et al., 2004). To solve the forces (Equation 21) and moments (Equation 22), Newton’s second as detailed by:

$$\sum \vec{R}_i + m\vec{g} = m\vec{a} \qquad \text{(Equation 21)}$$

$$\sum(\vec{M}_i + \vec{R}_i \times \vec{d}_i) = I\vec{\alpha} \qquad \text{(Equation 22)}$$

Where m is the mass of the segment, $\vec{g}$ is the acceleration due to gravity, $\vec{a}$ is the acceleration, *I* is the moment of inertia, $\vec{d}$ is moment arm of the force ($\vec{R}_i$), and $\vec{\alpha}$ is the angular acceleration. To begin the calculations, it is assumed that the hand (h) and the ball (b) are one segment before the ball release, so that the resultant force ($\vec{R}_{w-h}$) and the resultant moment ($\vec{M}_{w-h}$) acting on the wrist are solved for using Newton's second law (Equation 23 and 24, respectively). The resultant force and moment acting on the wrist are defined by:

$$\vec{R}_{w-h} = m_{h+b}(\vec{a}_{h+b} - \vec{g}) \qquad \text{(Equation 23)}$$

$$\vec{M}_{w-h} = I_{h+b}\vec{\alpha}_{h+b} - \vec{R}_{w-h} \times \vec{d}_{Rw-h} \qquad \text{(Equation 24)}$$

The next steps are continuing moving up the arm to elbow and then shoulder joint, the focus of this study. In accordance with Newton's third law, there are equal and opposite forces and moments acting on the wrist to the forearm ($\vec{R}_{w-fa} = -\vec{R}_{w-h}$, $\vec{M}_{w-fa} = -\vec{M}_{w-h}$). Then Newton's second law was used to find the resultant force ($\vec{R}_{e-fa}$) and the resultant moment ($\vec{M}_{e-fa}$) acting on the elbow (Equation 25 and 26, respectively). The resultant force and moment acting on the elbow are defined by:

$$\vec{R}_{e-fa} = m_{fa}(\vec{a}_{fa} - \vec{g}) - \vec{R}_{w-fa} \qquad \text{(Equation 25)}$$

$$\vec{M}_{e-fa} = I_{fa}\vec{\alpha}_{fa} - \vec{R}_{w-fa} \times \vec{d}_{Rw-fa} - \vec{R}_{e-fa} \times \vec{d}_{e-fa} - \vec{M}_{w-fa} \quad \text{(Equation 26)}$$

Then finally, following the same pattern for the shoulder joint. In accordance with Newton's third law, there are equal and opposite forces and moments acting on the elbow to the upper arm ($\vec{R}_{e-ua} = -\vec{R}_{e-fa}$, $\vec{M}_{e-ua} = -\vec{M}_{e-fa}$). Then Newton's second law was used to find the resultant force ($\vec{R}_{s-ua}$) and the resultant moment ($\vec{M}_{s-ua}$) acting on the shoulder (Equation 27 and 28, respectively). The resultant force and moment acting on the shoulder are defined by:

$$\vec{R}_{s-ua} = m_{ua}(\vec{a}_{ua} - \vec{g}) - \vec{R}_{e-ua} \quad \text{(Equation 27)}$$

$$\vec{M}_{s-ua} = I_{ua}\vec{\alpha}_{ua} - \vec{R}_{e-ua} \times \vec{d}_{Re-ua} - \vec{R}_{s-ua} \times \vec{d}_{Rs-ua} - \vec{M}_{e-ua} \quad \text{(Equation 28)}$$

A custom program (MATLAB; MathWorks) was created to calculate both the kinematics and kinetics (Fleisig et al., 1995; Fleisig et al., 1999; Zheng, 2003; Zheng et al., 1999). The motions were calculated as defined and the resultant forces and moments as defined. Further, components of elbow and shoulder joint forces and components of elbow and shoulder moments were determined. The shoulder joint loadings were anterior/posterior (AP), distal/proximal (PD), and superior/inferior (SI) force and abduction/adduction (AA), internal/external rotation (IE), and horizontal abduction/adduction (HAA) torque. The direction of the positive shoulder joint loading follows anterior, distal, and superior forces and abduction, internal rotation, and horizontal adduction torques (Figure 15). The direction of the negative shoulder joint loading would be the opposite forces and torques.

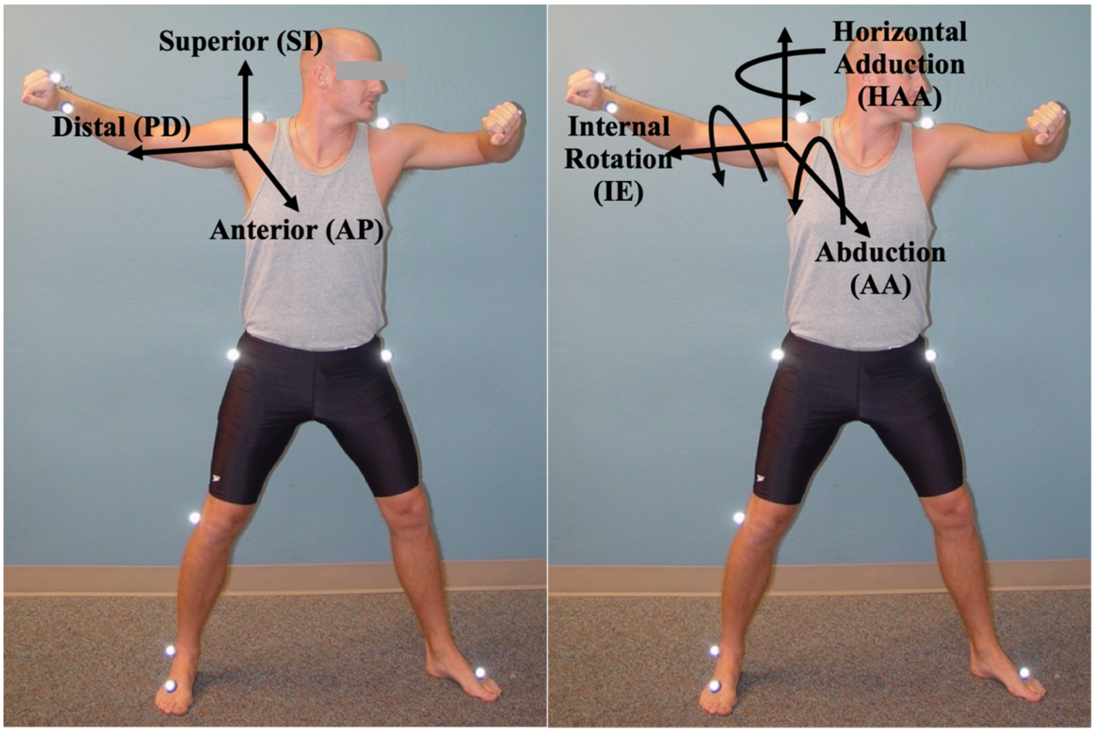

Figure 15: Shoulder (right shoulder in this figure) joint loading: 3 forces (left figure) and 3 torques (right figure) (Image from previous publication (Stokes et al., 2021)).

The elbow joint loadings were anterior/posterior (AP), medial/lateral (ML), and superior/inferior (SI) force and varus/valgus (VV) and extension/flexion (EF) torque. The direction of the positive elbow joint loading follows anterior, medial, and inferior forces and varus and extension torques (Figure 16). The direction of the negative elbow joint loading would be the opposite forces and torques.

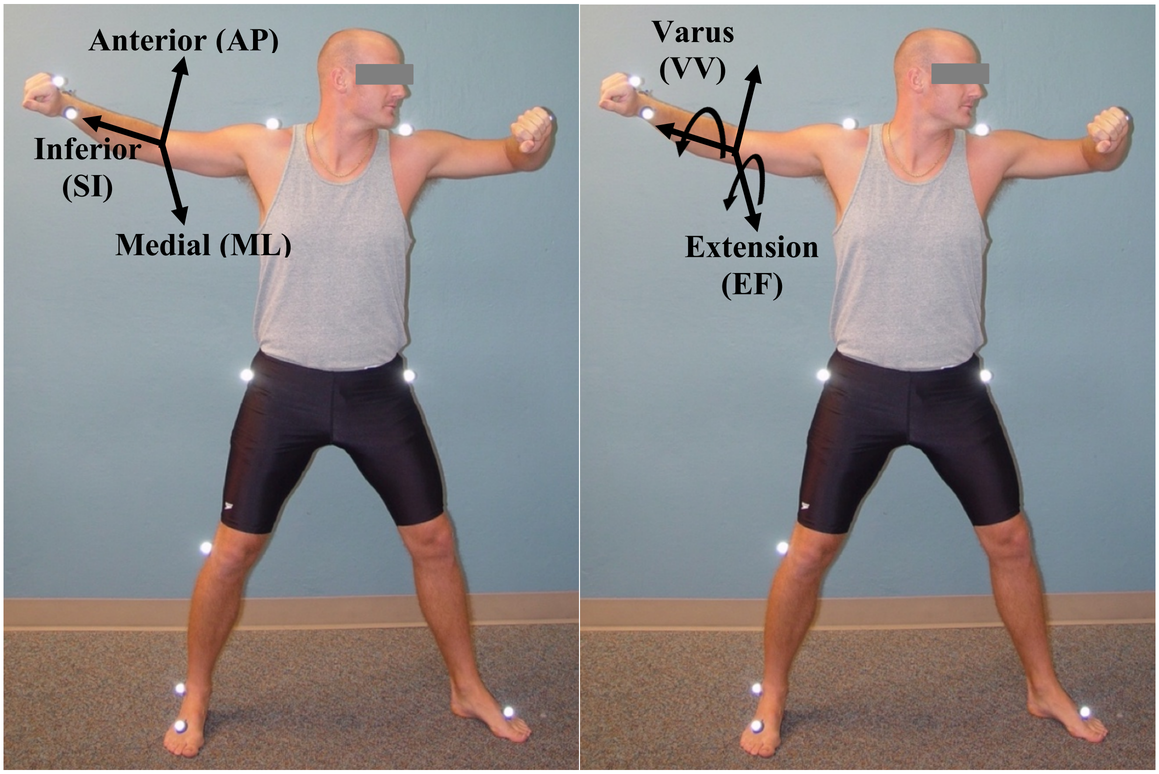

Figure 16: Elbow (right elbow in this figure) joint loading: 3 forces (left figure) and 2 torques (right figure).

4.4. Injury Questionnaire

The Injury Questionnaire that was developed in the first year was used in all years, which focuses on any pain and injuries that a pitcher may be experiencing currently as well as in the past 12 months. Pitchers who came to our lab filled out their injury questionnaire. Other pitchers who did not come the following years were requested to fill out injury questionnaire and return via mail or email or use the online survey site.

The Injury Questionnaire (Appendix D) was used to record the pitcher's team, class, height, weight, history of surgery, experience, and any current pain. The pitchers were classified in one of two groups depending on their responses (Figure 17). Pitchers who had an injury before biomechanical testing were referred to as having an injury history. Pitchers who had injuries after biomechanical testing noted it in a follow-up injury questionnaire and are referred to as having follow-up injury. Pitchers who had both injury history and follow-up injury are referred to having both injury history and follow-up injury.

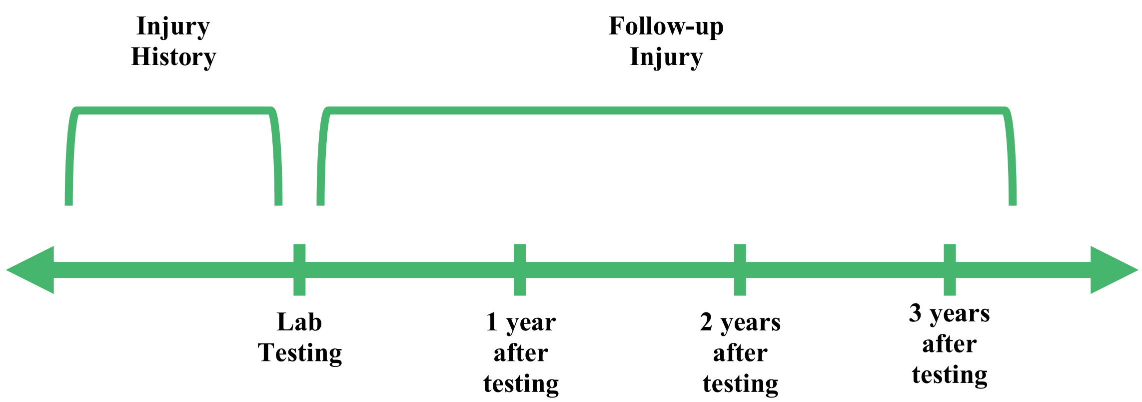

Figure 17: Injury questionnaire timeline defines anything before the lab testing as injury history and anything after in increments of one years as follow-up injury.

The total number of pitchers that were recruited and their return rate shows that the return rate in Division I was statistically significantly higher than Division II (Table 1). The pitchers answered the questionnaire with then were recruited in the lab and then each year following that participated either online or via mail. The pitchers dropped out of the study for variety of reasons, including graduation, transfer, dropping out of school, and many other reasons.

Table 1: Summary of all pitchers recruited, organized by division and how many years they followed up in the study.

	Pitchers Recruited	Follow-up Injury Year I	Follow-up Injury Year II	Follow-up Injury Year III
Division I	117	81	47	12
Division II	60	28	10	2
Total	177	109	57	14

4.5. Throwing Biomechanics Index for Baseball Pitching

The pitchers used for during the throwing biomechanics index included those with injury history, those with follow-up injury, those with injury history and follow-up injury, and those that had no injury and were high performing (Table 2). High performing is defined as those with ball speed 80 mph or greater. The biomechanics variables that are defined in section 4.3 Biomechanics of Baseball Pitching are used to determine the throwing biomechanics index; both kinematic and kinetic variables from foot angle to elbow torque and everything in between.

Table 2: Pitcher group count information for the throwing biomechanics index.

	Injury History	Follow-up Injury	Injury History and Follow-up Injury	No Injury and High Performing
n	38	25	8	31

A multinomial logistic regression was performed using SPSS to determine which factors were most influential and related to injury. The dependent variable is the injury variable which classifies each pitcher in their respective group of injury history, follow-up injury, injury history and follow-up injury, or no injury and high performing. The covariates were all the kinematic and kinetic variables. There were 15 statistically significant variables that include: stride length at foot contact, foot angle, knee angle at foot contact, maximum hip angular velocity, trunk forward angle, maximum spine lateral bend angular velocity, maximum external rotation angle, elbow angle at foot contact, maximum elbow angular velocity, peak anterior/posterior shoulder force, peak superior/inferior shoulder force, peak proximal/distal shoulder force, peak internal/external shoulder torque, resultant elbow force, and valgus/varus elbow torque.

The standards of the throwing biomechanics were determined based on the no injury and high performing group (ball speed > 80 mph). For each variable the mean and standard deviation was taken of the no injury and high performing group. From there each pitcher was compared to the mean of the no injury and high performing group for each variable. The z-score was determined for all pitchers for each variable (Equation 29) and can be defined by:

$$z = \frac{x - \mu}{\sigma} \quad \text{(Equation 29)}$$

Where z is the z-score, μ is the no injury and high performing group mean, σ is the no injury and high performing group standard deviation, and x is each pitcher's recorded variable value.

The z-score was used to calculate the probability following the normal distribution of the event occurring to give a continuous value which we defined as the index value for each variable. For the kinetic variables a one tailed approach was used because the lower the force or torque the better and the risk is found in the higher values (Equation 30, where P is the probability). For the kinematic variables a two tailed approach was used because the mean of the no injury and high performing group was the ideal value (Equation 31, where z is the z-score, and P is the probability). In this initial investigation all variables are weighted the same of 1 index point so a perfect score for the throwing biomechanics index is 15.

One tailed approach:

$$Index\ value = 1 - P \quad \text{(Equation 30)}$$

Two tailed approach:

$$Index\ value = 2 * \begin{pmatrix} z > 0 & 1 - P \\ z \leq 0 & P \end{pmatrix} \quad \text{(Equation 31)}$$

4.6. Data Analyses

The following section explains all data analysis that was performed for each of the five objectives. Prior to the objectives the summary of variables displays the mean ± standard deviation for all variables (demographic, shoulder exam, biomechanics) and all the counts for the injury variables for all pitchers in this study.

4.6.1. Objective 1 - Demographics vs. Shoulder Exam, Biomechanics, and Injury

The data analyses for Objective 1 - Demographics vs. Shoulder Exam, Biomechanics, and Injury includes a variety of tables. There is a table displaying the

Pearson correlation for comparing the demographic variables and shoulder exam variables. There is a table displaying the Pearson correlation for comparing the demographic variables and kinematic variables. There is a table displaying the Pearson correlation for comparing the demographic variables and kinetic variables. There is a table displaying the mean and standard deviation for the demographic variables for follow-up injury, injury history, no injury, and follow-up injury and injury history.

4.6.2. Objective 2 – Shoulder Exam vs. Biomechanics

The data analyses for Objective 2 – Shoulder Exam vs. Biomechanics includes a variety of tables and plots. There is a table displaying the Pearson correlation for comparing the dominant shoulder exam variables and kinematic variables. There is a table displaying the mean and standard deviation for the low, medium, and high groups of internal and external EPA for all kinematic variables. There is a table displaying the mean and standard deviation for the low, medium, and high groups of internal and external ROA for all kinematic variables. There is a table displaying the mean and standard deviation for the low, medium, and high groups of internal and external SRF for all kinematic variables. There is a table displaying the Pearson correlation for comparing the dominant shoulder exam variables and kinetic variables. There is a table displaying the mean and standard deviation for the low, medium, and high groups of internal and external EPA for all kinetic variables. There is a table displaying the mean and standard deviation for the low, medium, and high groups of internal and external ROA for all kinetic variables. There is a table displaying the mean and standard deviation for the low, medium, and high groups of internal and external SRF for all kinetic variables. There are figures of the three shoulder forces and torques for low, medium, and high internal EPA throughout the duration of the pitching cycle. There are figures of the three shoulder forces and torques for low, medium, and high external EPA throughout the duration of the pitching cycle.

4.6.3. Objective 3 – Injury vs. Shoulder Exam

The data analyses for Objective 3 – Injury vs. Shoulder Exam includes a variety of tables and plots. There is a table displaying the mean and standard deviation for all the shoulder exam variables for follow-up injury, injury history, no injury, and follow-up injury and injury history groups. There is a figure of bar graphs of internal and external EPA, ROA, and SRF for both arms for follow-up injury, injury history, no injury, and follow-up injury and injury history groups.

4.6.4. Objective 4 – Biomechanics vs. Injury

The data analyses for Objective 4 – Biomechanics vs. Injury includes a variety of tables and plots. There is a table displaying the mean and standard deviation for all the kinematic variables for follow-up injury, injury history, no injury, and follow-up injury and injury history groups. There is a table displaying the mean and standard deviation for all the kinetic variables for follow-up injury, injury history, no injury, and follow-up injury and injury history groups. There is a figure of pitching cycle plots of the no injury, shoulder follow-up injury, elbow follow-up injury, and both the shoulder and elbow follow-up injury groups for all the shoulder kinetic variables.

4.6.5. Objective 5 – Throwing Biomechanics Index for Baseball Pitching

The data analyses for Objective 5 – Throwing Biomechanics Index for Baseball Pitching includes a variety of tables and a bar graph. There is a bar graph that displays the throwing biomechanics index for the injury history, follow-up injury, both injury history and follow-up injury group, and the no injury and high performing group. There is a table that displays the mean and standard deviation for all the fifteen variables that make up the throwing biomechanics index score index for the injury history, follow-up injury, both injury history and follow-up injury group, and the no injury and high performing group. There are three different tables that investigate the Pearson correlation values when comparing pitcher demographic variables, performance (ball speed), and pitcher shoulder exam variables to the throwing biomechanics index, respectively.

4.7. Statistical Analyses

The following section explains all statistical analysis that was performed for each of the five objectives. All statistics were run using SPSS with alpha set to 0.05 (SPSS 27; IBM).

4.7.1. Objective 1 - Demographics vs. Shoulder Exam, Biomechanics, and Injury

The statistical analyses for Objective 1 – Demographics vs. Shoulder Exam, Biomechanics, and Injury includes Pearson correlation and one-way ANOVA tests. The first objective calculated the Pearson correlation values for demographics vs. shoulder exam and demographics vs. biomechanics. Further, mean ± standard deviation and one-way ANOVA with post-hoc tests for demographics vs. injury.

4.7.2. Objective 2 – Shoulder Exam vs. Biomechanics

The statistical analyses for Objective 2 – Shoulder Exam vs. Biomechanics include Pearson correlation and one-way ANOVA tests. The second objective calculated the Pearson correlation values for shoulder exam vs. kinematics and shoulder exam vs. kinetics variables. Further, mean ± standard deviation and one-way ANOVA with post-hoc tests for the dominant arm shoulder exam variables and kinetics and kinematics, respectively.

4.7.3. Objective 3 – Injury vs. Shoulder Exam

The statistical analyses for Objective 3 – Injury vs. Shoulder Exam includes one-way ANOVA and paired t-tests. The third objective calculated the mean ± standard deviation and one-way ANOVA with post-hoc tests for injury vs. shoulder exam. Further, the dominant and non-dominant arms were compared for internal and external EPA, ROA, and SRF for all injury groups.

4.7.4. Objective 4 – Biomechanics vs. Injury

The statistical analyses for Objective 4 – Biomechanics vs. Injury includes one-way ANOVA and paired t-tests. For the fourth objective we used mean ± standard deviation and one-way ANOVA with post-hoc tests to compare shoulder exam vs. kinematics and shoulder exam vs. kinetics. Further, the no injury, shoulder follow-up injury, elbow follow-up injury, and both the shoulder and elbow follow-up injury groups were compared with shoulder kinetic variables throughout the pitching cycle.

4.7.5. Objective 5 – Throwing Biomechanics Index for Baseball Pitching

The statistical analyses for Objective 5 – Throwing Biomechanics Index for Baseball Pitching includes one-way ANOVA, paired t-tests, and Pearson correlation tests. For the fifth objective we used mean ± standard deviation and one-way ANOVA with post-hoc tests to compare the throwing biomechanics index and the fifteen variables that comprises it among the injury history, follow-up injury, both injury history and follow-up injury group, and the no injury and high performing group. Further Pearson correlation tests were used to compare the throwing biomechanics index with pitcher demographic variables, performance (ball speed), and pitcher shoulder exam variables, respectively.

CHAPTER 5: RESULTS

The results chapter covers the summary of variables, objective 1 – demographics vs. shoulder exam, biomechanics, and injury, objective 2 – shoulder exam vs. biomechanics, objective 3 – injury vs. shoulder exam, objective 4 – biomechanics vs. injury, and objective 5 – throwing biomechanics index for baseball pitching. This chapter serves to explore all the outcomes of the study.

5.1. Summary of Variables

The summary of variables section provides a comprehensive list of all the variables with mean and standard deviation or the count that is representative of the whole study. This section breaks down the variables into demographic, shoulder exam, biomechanics, and injury. The section serves as a baseline to reference as further results are presented.

5.1.1. Demographics

The demographic variables include height, mass, body mass index (BMI), age, forearm length, upper arm length, and years played competitively (Table 3). All variables were quantitatively measured besides the years played competitively which was self-reported. The mean age of the pitcher in this study was 20.07 years old, who's height was 1.86 m (approximately 6-foot 1 inch) and 85.24 kg (approximately 188 pounds). Further, the average pitcher's upper arm was 7 cm longer than their forearm.

Table 3: The mean ± standard deviation of the demographic variables for the whole study.

Variables	Mean ± Standard Deviation
Height (m)	1.86±0.07
Mass (kg)	85.24±8.96
BMI (kg/m^2)	24.63±2.67
Age (years)	20.07±1.15
Forearm Length (cm)	28.14±1.73
Upper arm Length (cm)	35.58±2.82
Years Played Competitively	9.54±3.12

Further, demographic variables that are by count are the position (starter, reliever, or both) and division (I or II) (Table 4). The position or role of the pitcher was self-reported, and the division was determined based on the university or college that each pitcher attends, respectively. 37% of pitchers reported they were starters, 29% of pitchers reported they were relievers, and 34% of pitchers reported they were both starters and relievers. 66% of the study was Division I pitchers and the other 34% of the study was Division II pitchers.

Table 4: The count demographic variables of position and division for the whole study.

		Count
Position	Starter	65
	Reliever	52
	Both (Starter and Reliever)	60
Division	I	117
	II	60

5.1.2. Shoulder Exam Variables

The shoulder exam variables include internal EPA, internal ROA, internal SRF, external EPA, external ROA, external SRF, total ROM, and SEIR for both the dominant and non-dominant arms and additionally the bilateral difference of internal EPA and total ROM (Table 5). The non-dominant arm has the larger internal EPA, internal ROA, internal SRF, external SRF, and total ROM on average when compared to the dominant arm. The dominant arm has the larger external EPA, external ROA, and SEIR on average when compared to the non-dominant arm.

Table 5: The mean ± standard deviation of the shoulder exam variables (dominant and non-dominant arm and bilateral difference) for the whole study.

	Variables	**Mean ± Standard Deviation**
Dominant	Internal EPA (deg)	72.82±12.95
	Internal ROA (deg)	40.62±14.77
	Internal SRF (deg/Nm)	3.08±0.77
	External EPA (deg)	137.6±11.2
	External ROA (deg)	106.2±12.7
	External SRF (deg/Nm)	4.30±1.70
	Total ROM (deg)	210.4±16.7
	SEIR	1.95±0.42
Non-dominant	Internal EPA (deg)	84.08±12.63
	Internal ROA (deg)	53.20±13.92
	Internal SRF (deg/Nm)	3.15±0.90
	External EPA (deg)	129.3±13.4
	External ROA (deg)	96.70±12.70
	External SRF (deg/Nm)	4.49±1.50
	Total ROM (deg)	213.4±16.6
	SEIR	1.58±0.30
Bilateral Difference	Internal EPA (deg)	-11.27±12.09
	Total ROM (deg)	-3.01±14.54

5.1.3. Biomechanics Variables

The kinematic variables include the ball speed, stride length, lead foot angle, knee angle at foot contact, knee angle at ball release, elbow angle at foot contact, initial elbow extension angle, elbow angle at ball release, forward trunk angle, lateral trunk angle, shoulder abduction angle, shoulder horizontal adduction angle, maximum external rotation angle, spine lateral bend angle, maximum hip angular velocity, maximum trunk angular velocity, maximum elbow angular velocity, maximum shoulder internal rotation angular velocity, maximum shoulder horizontal adduction angular velocity, maximum spine axial rotation angular velocity, maximum spine lateral bend angular velocity, maximum hip linear velocity, and maximum shoulder linear velocity (Table 6).

Table 6: The mean ± standard deviation of the peak biomechanics variables (kinematics) for the whole study.

Variables	Mean ± Standard Deviation
Ball Speed (mph)	77.64±4.65
Stride Length (m)	0.68±0.05
Lead Foot Angle (deg)	-16.68±14.41
Knee Angle at Foot Contact (deg)	138.3±9.4
Knee Angle at Ball Release (deg)	146.0±13.7
Elbow Angle at Foot Contact (deg)	99.84±8.86
Initial Elbow Extension Angle (deg)	84.46±13.94
Elbow Angle at Ball Release (deg)	151.9±6.9
Forward Trunk Angle (deg)	27.74±8.91
Lateral Trunk Angle (deg)	21.27±9.39
Shoulder Abduction Angle (deg)	94.75±8.68
Shoulder Horizontal Adduction Angle (deg)	23.00±7.71
Maximum External Rotation Angle (deg)	174.2±11.4
Spine Lateral Bend Angle (deg)	1.63±7.15
Maximum Hip Angular Velocity (deg/s)	536.9±82.2
Maximum Trunk Angular Velocity (deg/s)	308.5±55.3
Maximum Elbow Angular Velocity (deg/s)	2249±2745
Maximum Shoulder Internal Rotation Angular Velocity (deg/s)	7479±1584
Maximum Shoulder Horizontal Adduction Angular Velocity (deg/s)	1002±212
Maximum Spine Axial Rotation Angular Velocity (deg/s)	507.5±116.0
Maximum Spine Lateral Bend Angular Velocity (deg/s)	301.5±64.5
Maximum Hip Linear Velocity (m/s)	1.86±0.35
Maximum Shoulder Linear Velocity (m/s)	3.59±0.43

The kinetic variables include the AP shoulder force, SI shoulder force, PD shoulder force, resultant shoulder force, shoulder force angle X, shoulder force angle Y, shoulder force angle Z, AA shoulder torque, IE shoulder torque, HAA shoulder torque, resultant shoulder torque, shoulder torque angle X, shoulder torque angle Y, shoulder torque angle Z, AP elbow force, ML elbow force, SI elbow force, resultant elbow force, elbow force angle X, elbow force angle Y, elbow force angle Z, VV elbow torque, EF elbow torque, resultant elbow torque, elbow torque angle X, and elbow torque angle Y (Table 7). The largest magnitude loadings were the PD shoulder force, AA shoulder torque, SI elbow force, and VV elbow torque.

Table 7: The mean ± standard deviation of the peak biomechanics variables (kinetics) for the whole study.

Variables	Mean ± Standard Deviation
AP Shoulder Force (N)	-445.5±97.9
SI Shoulder Force (N)	-363.4±104.4
PD Shoulder Force (N)	755.9±129.8
Resultant Shoulder Force (N)	957.0±152.8
Shoulder Force Angle X (deg)	37.50±5.05
Shoulder Force Angle Y (deg)	117.8±4.6
Shoulder Force Angle Z (deg)	112.4±5.6
AA Shoulder Torque (Nm)	-86.86±27.05
IE Shoulder Torque (Nm)	76.94±18.90
HAA Shoulder Torque (Nm)	80.15±20.40
Resultant Shoulder Torque (Nm)	142.6±32.7
Shoulder Torque Angle X (deg)	57.03±4.46
Shoulder Torque Angle Y (deg)	127.3±6.5
Shoulder Torque Angle Z (deg)	55.16±6.89
AP Elbow Force (N)	283.3±68.5
ML Elbow Force (N)	266.0±53.2
SI Elbow Force (N)	667.1±95.1
Resultant Elbow Force (N)	775.0±109.1
Elbow Force Angle X (deg)	69.94±2.70
Elbow Force Angle Y (deg)	68.52±4.24
Elbow Force Angle Z (deg)	30.35±3.77
VV Elbow Torque (Nm)	71.91±16.83
EF Elbow Torque (Nm)	-55.08±14.51
Resultant Elbow Torque (Nm)	91.02±20.34
Elbow Torque Angle X (deg)	37.39±5.94
Elbow Torque Angle Y (deg)	129.4±6.0

5.1.4. Injury Variables

The self-reported injuries occurred in the shoulder, elbow, or both the shoulder and the elbow (Table 8). There were 177 pitchers' data that was collected originally that is counted as history, 109 pitchers followed one year, 52 pitchers followed two years, and 14 pitchers followed three years. There was a much higher retention rate of Division I pitchers as compared to Division II pitchers. For the history, the most injuries occurred at the elbow. For the follow-up year one, most injuries occurred at the shoulder. For the follow-up year two, most injuries were tied at two for both the shoulder and the elbow. Finally, for the follow-up year three, most injuries occurred at the elbow.

Table 8: Summary of questionnaire pitcher breakdown for exclusively injuries for the whole study.

Throwing Arm Injury	Yes	No	Shoulder	Elbow	Both
	History				
Division I	17	100	5	7	5
Division II	6	54	3	2	1
Total	23	154	8	9	6
	Follow-up Year One				
Division I	10	71	5	4	1
Division II	3	25	2	1	0
Total	13	96	7	5	1
	Follow-up Year Two				
Division I	5	42	2	2	1
Division II	0	10	0	0	0
Total	5	52	2	2	1
	Follow-up Year Three				
Division I	1	11	0	1	0
Division II	0	2	0	0	0
Total	1	13	0	1	0

The self-reported surgeries occurred in the shoulder, elbow, or both the shoulder and the elbow (Table 9). For the history, the most surgeries occurred at the elbow. For the follow-up year one, most surgeries occurred at the elbow. For the follow-up year two, most surgeries occurred at the shoulder. Finally, for the follow-up year three, most surgeries occurred were tied at one for at the elbow and at both the shoulder and elbow.

Table 9: Summary of questionnaire pitcher breakdown for exclusively surgeries for the whole study.

Throwing Arm Surgery	Yes	No	Shoulder	Elbow	Both
	History				
Division I	16	101	6	9	1
Division II	7	53	3	4	0
Total	23	154	9	13	1
	Follow-up Year One				
Division I	5	76	2	3	0
Division II	2	26	1	1	0
Total	7	102	3	4	0
	Follow-up Year Two				
Division I	5	42	4	0	1
Division II	0	10	0	0	0
Total	5	52	4	0	1
	Follow-up Year Three				
Division I	2	10	0	1	1
Division II	0	2	0	0	0
Total	2	12	0	1	1

The summary of both the self-reported injuries and surgeries that occurred in the shoulder, elbow, or both the shoulder and the elbow (Table 10). For the history, the most injuries and surgeries occurred at the elbow. For the follow-up year one, most injuries and surgeries occurred at the shoulder. For the follow-up year two, most injuries and surgeries occurred at the shoulder. Finally, for the follow-up year three, most injuries and surgeries occurred at the elbow.

Table 10: Summary of questionnaire pitcher breakdown for both injuries and surgeries for the whole study.

	Yes	No	Shoulder	Elbow	Both
	History				
Division I	33	84	11	16	6
Division II	13	47	6	6	1
Total	46	131	17	22	7
	Follow-up Year One				
Division I	15	66	7	7	1
Division II	5	23	3	2	0
Total	20	99	10	9	1
	Follow-up Year Two				
Division I	10	37	6	2	2
Division II	0	10	0	0	0
Total	10	47	6	2	2
	Follow-up Year Three				
Division I	3	9	0	2	1
Division II	0	2	0	0	0
Total	3	11	0	2	1

5.2. Objective 1 – Demographics vs. Shoulder Exam, Biomechanics, and Injury

The objective 1 – demographics vs. shoulder exam, biomechanics, and injury provides a detailed look at each demographic vs. shoulder exam, demographics vs. biomechanics, and demographics vs. injury. The Pearson correlation, mean ± standard deviation and one-way ANOVA p-values values are calculated and reported. This section begins the exploration of this study in identifying all that is related in baseball pitching.

5.2.1. Demographics vs. Shoulder Exam

The Pearson correlation values for the demographic variables and shoulder exam variables had many statistically significant correlations (Table 11). The largest positive correlation was between dominant arm internal EPA and division level (R = 0.234) and the largest negative correlation was between dominant arm internal SRF and forearm length (R = -0.394). There were 13 statistically significant positive correlations and 32 statistically significant negative correlations.

Table 11: Pearson correlation (R) values for demographic variables and shoulder exam variables with a color array of deeper colors represent stronger correlations (purple negative correlation and green positive correlation), where $p < 0.05$ is shown bolded and with an asterisk (*).

			Height (m)	Mass (kg)	BMI (kg/m^2)	Age (years)	Forearm length (cm)	Upper arm length (cm)	Division	Years played	Follow-up (Years)
Dominant	Internal	EPA (deg)	0.006	0.074	0.044	0.105	0.011	**-0.220***	**0.234***	0.009	-0.118
		ROA (deg)	0.060	0.119	0.057	0.093	0.099	**-0.190***	**0.193***	0.020	**-0.166***
		SRF (deg/Nm)	**-0.194***	**-0.176***	-0.044	0.000	**-0.394***	**-0.226***	**0.183***	-0.045	0.102
	External	EPA (deg)	-0.071	-0.138	-0.082	**-0.155***	-0.082	0.021	-0.006	**-0.162***	-0.081
		ROA (deg)	-0.061	-0.079	-0.031	**-0.209***	**-0.225***	0.106	-0.090	**-0.281***	0.132
		SRF (deg/Nm)	-0.085	-0.087	-0.018	0.023	-0.093	**-0.246***	0.087	0.015	**-0.204***
		Total ROM (deg)	-0.043	-0.035	-0.021	-0.022	-0.046	**-0.157***	**0.178***	-0.101	-0.145
		SEIR	-0.028	-0.099	-0.056	**-0.150***	-0.033	**0.202***	**-0.153***	-0.040	0.050
Non-dominant	Internal	EPA (deg)	-0.052	0.008	0.052	-0.026	0.130	**-0.192***	**0.155***	0.089	-0.108
		ROA (deg)	-0.062	0.102	**0.162***	0.012	**0.179***	-0.100	0.099	**0.160***	-0.135
		SRF (deg/Nm)	-0.108	**-0.226***	**-0.149***	-0.087	**-0.290***	**-0.335***	0.112	-0.061	0.024
	External	EPA (deg)	-0.053	-0.123	-0.087	**-0.170***	-0.132	0.088	0.018	**-0.198***	-0.044
		ROA (deg)	-0.034	-0.089	-0.061	**-0.229***	**-0.158***	**0.171***	-0.083	**-0.251***	0.053
		SRF (deg/Nm)	-0.137	**-0.166***	-0.063	0.035	**-0.288***	**-0.200***	**0.155***	-0.089	-0.113
		Total ROM (deg)	-0.082	-0.093	-0.030	**-0.157***	-0.008	-0.075	0.132	-0.092	-0.118
		SEIR	0.036	-0.050	-0.085	-0.092	**-0.157***	**0.217***	-0.119	-0.144	0.063
Bilateral Difference		Internal EPA (deg)	0.060	0.071	-0.008	0.140	-0.124	-0.035	0.089	-0.083	-0.013
		Total ROM (deg)	0.044	0.066	0.010	**0.153***	-0.045	-0.095	0.053	-0.011	-0.032

5.2.2. Demographics vs. Biomechanics

The Pearson correlation values for the demographic variables and kinematic variables had many statistically significant correlations (Table 12). The largest positive correlation was between ball speed and forearm length (R = 0.268) and the largest negative correlation was between maximum external rotation angle and age (R = -0.233). There were 11 statistically significant positive correlations and 21 statistically significant negative correlations.

Table 12: Pearson correlation (R) values for demographic variables and kinematic variables with a color array of deeper colors represent stronger correlations (purple negative correlation and green positive correlation), where $p < 0.05$ is shown bolded and with an asterisk (*).

	Height (m)	Mass (kg)	BMI (kg/m^2)	Age (years)	Forearm length (cm)	Upper arm length (cm)	Division	Years played	Follow -up (Years)
Ball Speed (mph)	0.136	0.138	0.034	0.042	**0.268***	**0.249***	**-0.193***	0.092	0.034
Stride Length (m)	-0.122	0.134	**0.264***	-0.056	-0.011	0.096	-0.113	0.024	0.013
Lead Foot Angle (deg)	0.057	0.109	0.056	0.024	-0.125	-0.071	-0.005	-0.063	0.010
Knee Angle at Foot Contact (deg)	0.143	0.124	0.010	-0.025	**0.182***	0.070	-0.020	0.084	**-0.210***
Knee Angle at Ball Release (deg)	0.065	-0.058	-0.121	**-0.160***	0.115	-0.013	0.100	0.005	**-0.195***
Elbow Angle at Foot Contact (deg)	-0.012	-0.038	-0.026	-0.068	0.000	0.116	-0.145	-0.022	0.074
Initial Elbow Extension Angle (deg)	-0.089	-0.038	0.034	-0.028	-0.109	-0.028	-0.096	0.083	0.061
Elbow Angle at Ball Release (deg)	-0.036	-0.085	-0.050	-0.124	-0.080	0.119	0.057	**-0.191***	0.049
Forward Trunk Angle (deg)	0.037	-0.015	-0.039	-0.127	0.106	-0.033	0.085	-0.073	-0.074
Lateral Trunk Angle (deg)	0.052	-0.071	-0.115	-0.114	0.078	0.074	0.061	-0.097	0.055
Shoulder Abduction Angle (deg)	-0.022	-0.054	-0.049	0.041	-0.129	-0.078	0.064	-0.110	0.081
Shoulder Horizontal Adduction Angle (deg)	**-0.163***	-0.069	0.053	0.142	-0.124	-0.101	0.005	0.073	-0.121
Maximum External Rotation Angle (deg)	-0.013	-0.108	-0.087	**-0.233***	0.042	0.091	-0.047	**-0.159***	-0.047

Spine Lateral Bend Angle (deg)	-0.082	-0.015	0.059	0.084	0.072	-0.139	0.138	0.058	-0.091
Maximum Hip Angular Velocity (deg/s)	-0.019	**-0.174***	**-0.170***	**-0.195***	-0.063	0.119	-0.089	0.008	0.028
Maximum Trunk Angular Velocity (deg/s)	**0.156***	**0.148***	0.019	0.039	0.118	0.037	-0.004	-0.052	-0.021
Maximum Elbow Angular Velocity (deg/s)	-0.077	-0.100	-0.045	-0.068	-0.017	-0.008	0.053	**-0.159***	0.026
Maximum Shoulder Internal Rotation Angular Velocity (deg/s)	-0.073	**-0.168***	-0.115	**-0.163***	**-0.155***	-0.055	**0.160***	**-0.225***	0.086
Maximum Shoulder Horizontal Adduction Angular Velocity (deg/s)	**-0.148***	-0.136	-0.014	-0.083	-0.131	0.045	-0.001	-0.145	-0.031
Maximum Spine Axial Rotation Angular Velocity (deg/s)	**-0.179***	-0.101	0.046	0.006	-0.091	-0.053	0.020	**-0.157***	-0.056
Maximum Spine Lateral Bend Angular Velocity (deg/s)	0.028	0.029	0.010	**-0.162***	0.098	-0.064	0.050	0.102	-0.002
Maximum Hip Linear Velocity (m/s)	0.127	0.007	-0.077	-0.016	**0.169***	**0.172***	**-0.163***	0.080	-0.077
Maximum Shoulder Linear Velocity (m/s)	0.100	0.053	-0.020	-0.103	**0.194***	**0.162***	0.011	0.037	-0.095

The Pearson correlation values for the demographic variables and kinetic variables had many statistically significant correlations (Table 13). The largest positive correlation was between elbow SI force and mass (R = 0.276) and the largest negative correlation was between shoulder SI force and mass (R = -0.215). There were 25 statistically significant positive correlations and 7 statistically significant negative correlations.

Table 13: Pearson correlation (R) values for demographic variables and kinetic variables with a color array of deeper colors represent stronger correlations (purple negative correlation and green positive correlation), where $p < 0.05$ is shown bolded and with an asterisk (*).

			Height (m)	Mass (kg)	BMI (kg/m^2)	Age (years)	Forearm length (cm)	Upper arm length (cm)	Division	Years played	Follow-up (Years)
Shoulder	Force (N)	AP	-0.121	**-0.188***	-0.095	-0.038	**-0.160***	0.081	-0.061	-0.139	0.017
		SI	**-0.183***	**-0.215***	-0.064	0.017	-0.104	-0.054	0.029	-0.100	0.014
		PD	0.053	**0.204***	**0.171***	-0.042	0.139	0.054	-0.086	**0.153***	-0.041
		Resultant	0.119	**0.249***	**0.160***	-0.019	**0.174***	0.032	-0.043	**0.167***	-0.041
	Torque	AA	-0.102	-0.054	0.018	0.071	-0.123	0.006	-0.125	-0.019	0.009
		IE	0.115	0.142	0.048	0.008	**0.172***	-0.065	0.087	0.099	-0.062
		HAA	0.142	0.132	0.028	-0.074	**0.245***	0.099	-0.065	0.124	0.050
		Resultant	0.140	0.120	0.015	-0.059	**0.205***	0.011	0.062	0.094	-0.010
Elbow	Force (N)	AP	0.107	**0.172***	0.082	-0.012	0.093	0.018	-0.121	**0.186***	-0.071
		ML	0.146	0.145	0.029	-0.057	0.108	-0.058	0.098	0.017	-0.036
		SI	0.133	**0.276***	**0.175***	-0.075	**0.198***	0.006	-0.073	0.140	-0.034
		Resultant	0.147	**0.273***	**0.158***	-0.068	**0.187***	-0.003	-0.062	**0.151***	-0.047
	Torque	VV	**0.161***	**0.178***	0.047	-0.037	**0.195***	-0.032	0.071	0.089	-0.111
		EF	-0.144	**-0.178***	-0.057	-0.001	**-0.195***	-0.044	0.108	**-0.201***	0.116
		Resultant	**0.163***	**0.196***	0.062	-0.022	**0.211***	-0.003	0.001	0.145	-0.121

5.2.3. Demographics vs. Injury

There were relationships between the shoulder exam variables and injury variables (Table 14). There were two statistically significant relationships between the division and follow-up (years) and injury variables, respectively. For division and the injury variables, the no injury group had the largest division level, and both follow-up injury and injury history group had the smallest division level ($p = 0.040$, with no statistically significant post-hoc tests). For the follow-up (years) and the injury variables, the follow-up injury group had the largest follow-up time, and the no injury group had the smallest follow-up time ($p = 0.014$, with the largest and smallest having statistically significant post-hoc tests). There were some variations among the other variables but no statistically significant differences.

Table 14: The mean ± standard deviation of the demographic variables and for follow-up injury, injury history, no injury, and follow-up injury and injury history, where $p < 0.05$ is bolded and asterisk (*) indicates a statistically significant post-hoc test.

	Follow-up Injury	Injury History	No Injury	Follow-up injury and Injury History	p
Height (m)	1.87±0.10	1.86±0.06	1.86±0.07	1.85±0.04	0.932
Mass (kg)	87.00±9.62	86.32±7.04	84.43±9.25	85.40±11.36	0.500
BMI (kg/m^2)	25.11±4.13	24.88±1.92	24.41±2.49	24.87±2.48	0.600
Age (years)	19.96±1.10	20.16±1.20	20.08±1.18	20.00±0.93	0.925
Forearm length (cm)	27.90±1.54	28.17±1.78	28.18±1.81	28.13±0.99	0.907
Upper arm length (cm)	35.58±2.66	35.59±2.44	35.48±3.00	37.00±2.56	0.540
Division Level	**1.20±0.41**	**1.34±0.48**	**1.41±0.49**	**1.00±0.00**	**0.040**
Years played	9.52±2.69	9.79±2.91	9.42±3.33	10.00±2.98	0.907
Follow-up (years)	**1.56±0.71***	**1.00±1.01**	**0.88±1.00***	**1.25±0.46**	**0.014**

5.3. Objective 2 – Shoulder Exam vs. Biomechanics

The objective 2 – shoulder exam vs. biomechanics provides a detailed look at each shoulder exam vs. kinematics and shoulder exam vs. kinetics. The Pearson correlation values are calculated and reported. This section begins the investigation of the three pillars in baseball pitching.

5.3.1. Shoulder Exam vs. Kinematics

The Pearson correlation values for the dominant shoulder exam variables and kinematic variables had many statistically significant correlations (Table 15). The largest positive correlation was between maximum external rotation angle and external EPA (R = 0.356) and the largest negative correlation was between shoulder abduction angle and external EPA (R = -0.203). There were 21 statistically significant positive correlations and 7 statistically significant negative correlations.

Table 15: Pearson correlation (R) values for dominant shoulder exam variables and kinematic variables with a color array of deeper colors represent stronger correlations (purple negative correlation and green positive correlation), where $p < 0.05$ is shown bolded and with an asterisk (*).

	Internal			External				
	EPA	ROA	SRF	EPA	ROA	SRF	Total ROM	SEIR
Ball Speed (mph)	-0.076	-0.033	-0.099	0.060	-0.054	-0.008	-0.018	0.101
Stride Length (m)	-0.072	-0.034	-0.135	**0.180***	**0.163***	0.050	0.064	0.125
Lead Foot Angle (deg)	**0.194***	0.138	0.037	-0.008	0.039	-0.007	0.145	**-0.194***
Knee Angle at Foot Contact (deg)	**0.179***	**0.219***	-0.070	0.107	-0.076	**0.214***	**0.211***	-0.088
Knee Angle at Ball Release (deg)	**0.205***	**0.224***	-0.012	0.112	-0.024	0.030	**0.234***	-0.116
Elbow Angle at Foot Contact (deg)	-0.079	-0.087	0.018	0.092	0.084	0.078	0.000	0.091
Initial Elbow Extension Angle (deg)	-0.015	-0.049	0.065	0.003	0.067	-0.002	-0.010	-0.005
Elbow Angle at Ball Release (deg)	-0.108	-0.139	0.052	**0.184***	**0.265***	-0.046	0.040	0.137
Forward Trunk Angle (deg)	0.025	0.056	-0.013	0.124	-0.008	0.070	0.102	0.055
Lateral Trunk Angle (deg)	-0.104	-0.089	-0.053	0.062	0.056	-0.078	-0.039	0.118
Shoulder Abduction Angle (deg)	-0.065	0.016	-0.062	**-0.203***	-0.121	0.089	**-0.186***	-0.002
Shoulder Horizontal Adduction Angle (deg)	-0.025	0.012	0.022	-0.142	**-0.171***	0.084	-0.114	-0.022
Maximum External Rotation Angle (deg)	-0.061	-0.007	-0.011	**0.356***	**0.224***	0.117	**0.191***	**0.197***

Spine Lateral Bend Angle (deg)	**0.167***	**0.199***	0.007	-0.040	-0.088	-0.046	0.103	**-0.152***
Maximum Hip Angular Velocity (deg/s)	0.076	-0.005	**0.191***	0.095	0.092	-0.031	0.122	-0.035
Maximum Trunk Angular Velocity (deg/s)	-0.076	-0.035	**-0.149***	-0.054	-0.090	-0.029	-0.095	0.040
Maximum Elbow Angular Velocity (deg/s)	-0.031	0.042	-0.083	0.081	0.013	0.048	0.030	0.057
Maximum Shoulder Internal Rotation Angular Velocity (deg/s)	0.094	0.090	0.075	0.110	0.085	0.084	0.146	-0.051
Maximum Shoulder Horizontal Adduction Angular Velocity (deg/s)	-0.035	0.019	0.032	0.062	0.070	0.009	0.014	0.057
Maximum Spine Axial Rotation Angular Velocity (deg/s)	0.004	0.036	0.028	0.089	0.029	0.072	0.063	0.061
Maximum Spine Lateral Bend Angular Velocity (deg/s)	-0.007	-0.047	-0.039	0.072	0.026	-0.014	0.043	0.041
Maximum Hip Linear Velocity (m/s)	-0.079	0.030	**-0.195***	0.061	-0.048	0.098	-0.020	0.072
Maximum Shoulder Linear Velocity (m/s)	-0.075	-0.014	-0.072	**0.189***	0.109	-0.030	0.069	**0.152***

The Pearson correlation values for the bilateral shoulder exam variables and kinematic variables had several statistically significant correlations. There were two statistically significant positive correlations and two statistically significant negative correlations. The statistically significant positive correlations were lead foot angle and bilateral difference total ROM (R = 0.154) and maximum shoulder internal rotation angular velocity and bilateral difference internal EPA (R = 0.154). The statistically significant negative correlations were maximum shoulder horizontal adduction angle and bilateral difference total ROM (R = -0.168) and maximum hip linear velocity and bilateral difference internal EPA (R = -0.162).

The ANOVA tests comparing low, medium, and high internal and external EPA groups, respectively, with kinematic variables had several statistically significant differences (Table 16). For the internal EPA comparisons, there were two statistically significant differences found in the lead foot angle and the knee angle at ball release. For the external EPA comparisons, there were four statistically significant differences found in the elbow angle at ball release, shoulder abduction angle, maximum external rotation angle, and maximum shoulder linear velocity.

Table 16: Comparing across mean ± standard deviation low, medium, and high groups for internal and external EPA, respectively for all kinematic variables. Where bold for $p < 0.05$ and statistically significant post-hoc tests a: Low vs. Medium, b: Low vs. High, and c: Medium vs. High.

	Internal EPA			External EPA		
	Low	Medium	High	Low	Medium	High
Ball Speed (mph)	78.69±3.77	77.17±4.71	79.22±4.83	77.11±4.09	77.66±4.86	78.09±4.47
Stride Length (m)	0.68±0.05	0.68±0.05	0.68±0.03	0.68±0.04	0.68±0.05	0.70±0.04
Lead Foot Angle (deg)	**-23.2±20.5[b]**	**-16.31±13.0**	**-11.5±11.9[b]**	-15.22±11.5	-17.18±16.2	-16.32±9.38
Knee Angle at Foot Contact (deg)	137.2±12.2	138.1±8.7	140.6±10.2	137.9±9.0	138.1±9.7	139.6±8.9
Knee Angle at Ball Release (deg)	**143.0±11.1[b]**	**145.2±13.7[c]**	**154.0±14.7[bc]**	144.8±11.5	145.2±14.3	150.0±13.3
Elbow Angle at Foot Contact (deg)	101.5±19.4	100.0±18.8	96.81±19.41	98.29±17.62	99.75±19.75	101.8±17.0
Initial Elbow Extension Angle (deg)	82.47±12.94	85.24±14.37	82.11±12.44	85.72±11.60	84.46±14.80	83.15±13.11
Elbow Angle at Ball Release (deg)	152.3±6.0	152.1±7.2	150.6±6.4	**149.2±7.1**	**152.4±6.7**	**152.8±7.4**
Forward Trunk Angle (deg)	28.38±7.96	27.11±9.49	30.80±5.24	26.15±8.78	27.67±9.35	29.66±7.12
Lateral Trunk Angle (deg)	23.91±10.44	20.70±9.38	21.63±7.95	19.31±9.50	21.47±9.26	22.58±9.76
Shoulder Abduction Angle (deg)	95.02±7.78	94.98±8.55	93.08±10.47	**96.33±8.43[b]**	**95.95±8.14[c]**	**88.70±8.56[bc]**
Shoulder Horizontal Adduction Angle (deg)	23.03±7.57	23.43±7.81	20.43±7.03	25.15±8.40	22.88±7.11	21.21±8.77
Maximum External Rotation Angle (deg)	176.9±9.9	173.4±11.6	175.6±11.5	**167.1±12.5[ab]**	**174.8±10.2[a]**	**179.3±11.3[b]**
Spine Lateral Bend Angle (deg)	0.37±7.58	1.39±6.84	4.50±7.98	2.91±5.77	1.26±7.48	1.69±7.23

Maximum Hip Angular Velocity (deg/s)	526.9±74.6	534.3±82.2	563.2±88.8	525.3±80.7	534.5±84.9	557.5±71.6
Maximum Trunk Angular Velocity (deg/s)	309.6±57.8	309.9±56.5	299.0±46.1	311.6±58.1	309.1±57.4	303.1±44.7
Maximum Elbow Angular Velocity (deg/s)	2269±237	2242±277	2267±311	2204±234	2253±285	2281±277
Maximum Shoulder Internal Rotation Angular Velocity (deg/s)	7031±742	7503±1606	7849±2047	7259±1390	7548±156	7452±1850
Maximum Shoulder Horizontal Adduction Angular Velocity (deg/s)	1034±171	1000±224	978±175	990±200	999±209	1024±235
Maximum Spine Axial Rotation Angular Velocity (deg/s)	537.0±100.1	501.4±120.5	510.6±103.6	507.9±77.6	502.2±111.9	526.7±158.1
Maximum Spine Lateral Bend Angular Velocity (deg/s)	294.9±60.1	303.3±66.2	298.6±61.3	291.2±60.7	302.8±66.0	307.3±63.8
Maximum Hip Linear Velocity (m/s)	1.88±0.38	1.86±0.36	1.86±0.25	1.84±0.32	1.87±0.39	1.84±0.21
Maximum Shoulder Linear Velocity (m/s)	3.60±0.38	3.57±0.44	3.66±0.46	**3.55±0.46**	**3.54±0.40**[c]	**3.79±0.44**[c]

The ANOVA tests comparing low, medium, and high internal and external ROA groups, respectively, with kinematic variables had several statistically significant differences (Table 17). For the internal ROA comparisons, there were two statistically significant differences found in the ball speed and knee angle at ball release. For the external ROA comparisons, there were four statistically significant differences found in the stride length, elbow angle at ball release, shoulder abduction angle, and maximum external rotation angle.

Table 17: Comparing across mean ± standard deviation low, medium, and high groups for internal and external ROA, respectively for all kinematic variables. Where bold for p < 0.05 and statistically significant post-hoc tests a: Low vs. Medium, b: Low vs. High, and c: Medium vs. High.

	Internal ROA			External ROA		
	Low	Medium	High	Low	Medium	High
Ball Speed (mph)	**79.46±3.48[a]**	**77.16±4.80[a]**	**77.73±4.75**	77.70±4.38	77.54±4.98	77.95±3.54
Stride Length (m)	0.69±0.06	0.68±0.05	0.69±0.04	**0.65±0.07[ab]**	**0.69±0.04[a]**	**0.69±0.04[b]**
Lead Foot Angle (deg)	-22.0±19.0	-16.0±13.2	-14.1±12.9	-20.9±22.3	-15.8±13.0	-16.5±10.1
Knee Angle at Foot Contact (deg)	135.8±11.1	138.2±8.9	141.6±9.1	139.4±14.7	137.8±7.9	139.3±9.1
Knee Angle at Ball Release (deg)	**139.9±10.4[b]**	**146.7±13.0**	**149.4±17.9[b]**	145.1±16.8	145.4±12.9	148.8±14.2
Elbow Angle at Foot Contact (deg)	101.8±20.3	100.3±18.3	95.75±19.65	97.00±17.99	99.61±19.57	103.2±16.8
Initial Elbow Extension Angle (deg)	80.95±13.35	86.18±14.57	80.92±10.39	83.93±12.19	83.78±14.71	87.54±12.18
Elbow Angle at Ball Release (deg)	150.7±6.2	152.6±7.2	150.1±6.1	**148.1±5.7[ab]**	**152.3±6.9[a]**	**153.7±7.1[b]**
Forward Trunk Angle (deg)	29.94±8.52	26.89±9.27	29.03±7.36	28.02±8.12	27.68±9.16	27.74±8.88
Lateral Trunk Angle (deg)	23.68±9.41	21.04±9.57	19.67±8.36	20.01±8.54	21.56±9.55	21.25±9.68
Shoulder Abduction Angle (deg)	95.79±7.16	94.58±8.85	94.35±9.61	**94.77±8.29**	**96.10±8.57[c]**	**89.56±7.65[c]**
Shoulder Horizontal Adduction Angle (deg)	23.99±7.43	22.58±7.74	23.70±8.01	25.82±9.31	22.83±6.98	21.20±8.46
Maximum External Rotation Angle (deg)	176.3±11.2	173.3±11.4	175.4±11.4	**169.7±12.2[b]**	**174.4±10.6**	**177.2±12.6[b]**
Spine Lateral Bend Angle (deg)	0.27±7.38	1.60±6.84	3.21±8.08	3.41±8.79	1.02±6.66	2.43±7.30

Maximum Hip Angular Velocity (deg/s)	531.6±6.39	540.8±82.5	525.9±98.4	518.9±91.5	535.8±81.5	556.6±74.5
Maximum Trunk Angular Velocity (deg/s)	317.6±57.0	307.6±56.7	302.3±47.6	314.3±51.7	310.0±58.5	297.7±45.2
Maximum Elbow Angular Velocity (deg/s)	2300±229	2230±297	2277±209	2204±243	2269±289	2212±242
Maximum Shoulder Internal Rotation Angular Velocity (deg/s)	7266±1156	7502±1585	7610±1970	6904±1214	7650±1674	7323±1411
Maximum Shoulder Horizontal Adduction Angular Velocity (deg/s)	1015±201	992±219	1029±191	984±246	989±201	1066±213
Maximum Spine Axial Rotation Angular Velocity (deg/s)	501.3±89.6	504.6±122.5	526.8±113.7	528.0±124.7	500.8±96.3	515.6±168.2
Maximum Spine Lateral Bend Angular Velocity (deg/s)	298.6±52.8	304.8±69.0	290.6±56.4	295.8±61.2	303.7±69.6	298.0±45.4
Maximum Hip Linear Velocity (m/s)	1.86±0.31	1.84±0.36	1.94±0.33	1.85±0.53	1.87±0.32	1.85±0.25
Maximum Shoulder Linear Velocity (m/s)	3.65±0.41	3.57±0.43	3.61±0.45	3.50±0.51	3.58±0.42	3.68±0.40

The ANOVA tests comparing low, medium, and high internal and external SRF groups, respectively, with kinematic variables had several statistically significant differences (Table 18). For the internal SRF comparisons, there were two statistically significant differences found in the maximum shoulder horizontal adduction angular velocity and maximum hip linear velocity. For the external SRF comparisons, there were two statistically significant differences found in the knee angle at foot contact and forward trunk angle.

Table 18: Comparing across mean ± standard deviation low, medium, and high groups for internal and external SRF, respectively for all kinematic variables. Where bold for $p < 0.05$ and statistically significant post-hoc tests a: Low vs. Medium, b: Low vs. High, and c: Medium vs. High.

	Internal SRF			External SRF		
	Low	Medium	High	Low	Medium	High
Ball Speed (mph)	78.94±4.79	77.48±4.54	77.28±5.05	77.46±4.18	77.71±4.76	77.44±4.64
Stride Length (m)	0.70±0.03	0.68±0.05	0.67±0.04	0.68±0.03	0.69±0.05	0.68±0.06
Lead Foot Angle (deg)	-19.16±7.90	-16.41±15.89	-15.80±11.04	-16.08±11.36	-16.52±12.07	-17.78±23.26
Knee Angle at Foot Contact (deg)	139.4±9.0	138.0±9.7	138.8±8.7	**137.0±7.2[b]**	**137.2±9.2[c]**	**143.9±10.1[bc]**
Knee Angle at Ball Release (deg)	147.6±15.5	145.1±13.8	148.7±11.7	146.4±14.2	145.3±12.9	148.2±16.8
Elbow Angle at Foot Contact (deg)	94.00±16.88	101.5±19.0	97.11±19.40	98.19±19.34	99.65±18.65	101.8±19.9
Initial Elbow Extension Angle (deg)	78.32±13.50	85.60±13.72	84.35±14.48	85.30±13.34	84.47±14.10	83.82±14.11
Elbow Angle at Ball Release (deg)	150.7±6.6	152.1±7.1	152.0±6.6	154.7±7.0	151.6±6.8	151.0±7.3
Forward Trunk Angle (deg)	28.41±8.94	27.37±9.40	28.92±6.24	**22.51±10.22[a]**	**28.93±8.53[a]**	**26.63±8.19**
Lateral Trunk Angle (deg)	22.23±10.32	21.23±9.12	20.63±10.12	20.60±9.01	22.01±9.34	18.69±9.70
Shoulder Abduction Angle (deg)	94.74±10.53	94.99±8.11	93.65±9.79	92.63±6.70	94.62±9.42	96.84±6.13
Shoulder Horizontal Adduction Angle (deg)	20.66±8.06	23.22±7.22	23.98±9.44	21.50±7.48	22.99±7.69	24.14±8.03
Maximum External Rotation Angle (deg)	173.6±10.2	173.9±11.6	176.0±11.3	174.0±12.7	174.1±11.7	174.4±9.2

Spine Lateral Bend Angle (deg)	-0.07±6.69	1.70±7.20	2.76±7.23	3.47±5.52	1.18±6.79	2.17±9.34
Maximum Hip Angular Velocity (deg/s)	518.2±75.3	534.9±84.7	562.1±72.0	549.2±80.1	537.8±78.9	524.1±97.3
Maximum Trunk Angular Velocity (deg/s)	322.5±39.7	309.7±58.0	291.0±50.6	312.3±45.1	308.5±55.7	305.8±61.7
Maximum Elbow Angular Velocity (deg/s)	2337±320	2236±271	2238±245	2227±197	2253±286	2252±283
Maximum Shoulder Internal Rotation Angular Velocity (deg/s)	7152±1401	7530±1612	7520±1623	7271±1088	7497±1527	7558±2089
Maximum Shoulder Horizontal Adduction Angular Velocity (deg/s)	**982±172**	**985±218**[c]	**1099±191**[c]	1006±172	1004±213	991±236
Maximum Spine Axial Rotation Angular Velocity (deg/s)	517.3±122.3	504.5±110.8	513.4±136.7	515.8±134.5	499.3±109.1	535.9±128.3
Maximum Spine Lateral Bend Angular Velocity (deg/s)	308.8±51.7	302.8±66.7	289.0±64.5	299.3±62.5	302.7±63.5	298.2±71.8
Maximum Hip Linear Velocity (m/s)	**2.01±0.32**[b]	**1.86±0.36**	**1.74±0.28**[b]	1.93±0.36	1.84±0.31	1.90±0.48
Maximum Shoulder Linear Velocity (m/s)	3.63±0.37	3.60±0.44	3.50±0.41	3.65±0.39	3.60±0.41	3.50±0.53

5.3.2. Shoulder Exam vs. Kinetics

The Pearson correlation values for the dominant shoulder exam variables and kinetic variables had many statistically significant correlations (Table 19). The largest positive correlation was between elbow AP force and external SRF (R = 0.230) and the largest negative correlation was between shoulder IE torque and external ROA (R = -0.245). There were 13 statistically significant positive correlations and 14 statistically significant negative correlations.

Table 19: Pearson correlation (R) values for dominant shoulder exam variables and kinetic variables with a color array of deeper colors represent stronger correlations (purple negative correlation and green positive correlation), where $p < 0.05$ is shown bolded and with an asterisk (*).

			Internal			External				
			EPA	ROA	SRF	EPA	ROA	SRF	Total ROM	SEIR
Shoulder	Force	AP	-0.092	-0.078	0.054	0.115	**0.190***	-0.061	0.006	0.132
		SI	-0.113	-0.103	0.031	0.037	**0.174***	-0.133	-0.062	0.127
		PD	0.028	0.050	-0.128	-0.089	**-0.203***	0.069	-0.038	-0.078
		Resultant	0.074	0.083	-0.115	-0.100	**-0.237***	0.101	-0.009	-0.123
	Torque	AA	-0.003	-0.049	0.090	0.070	0.137	-0.096	0.045	0.032
		IE	**0.178***	**0.193***	-0.040	-0.117	**-0.245***	**0.164***	0.059	**-0.191***
		HAA	-0.072	-0.044	-0.102	-0.090	-0.118	-0.026	-0.116	0.004
		Resultant	0.043	0.081	-0.093	-0.106	**-0.195***	0.094	-0.038	-0.083
Elbow	Force	AP	0.063	0.119	-0.142	-0.019	**-0.176***	**0.230***	0.036	-0.048
		ML	0.128	0.124	-0.002	-0.117	**-0.195***	0.123	0.021	**-0.155***
		SI	0.050	0.083	-0.119	-0.046	**-0.177***	0.065	0.008	-0.069
		Resultant	0.078	0.113	-0.119	-0.059	**-0.210***	0.126	0.021	-0.093
	Torque	VV	**0.153***	**0.187***	-0.069	-0.101	**-0.220***	**0.149***	0.051	**-0.167***
		EF	-0.073	-0.130	**0.164***	0.042	**0.205***	**-0.212***	-0.029	0.061
		Resultant	0.136	**0.179***	-0.111	-0.086	**-0.235***	**0.191***	0.048	-0.139

The Pearson correlation values for the bilateral shoulder exam variables and kinetic variables had one statistically significant correlation. There was a statistically significant positive between elbow AP force and bilateral difference total ROM (R = 0.152).

The ANOVA tests comparing low, medium, and high internal and external EPA groups, respectively, with kinetic variables had several statistically significant differences (Table 20). For the internal EPA comparisons, there were two statistically significant differences found in the superior/inferior shoulder force and resultant shoulder force. For the external EPA comparisons, there were no statistically significant differences found.

Table 20: Comparing across mean ± standard deviation low, medium, and high groups for internal and external EPA, respectively. Where bold for $p < 0.05$ and statistically significant post-hoc tests a: Low vs. Medium, b: Low vs. High, and c: Medium vs. High.

			Internal EPA			External EPA		
			Low	Medium	High	Low	Medium	High
Shoulder	Force (N)	AP	-409.7±102.9	-450.2±95.7	-458.1±100.7	-468.8±89.6	-441.4±98.8	-436.3±102.5
		SI	**-315.6±90.8[a]**	**-373.9±100.1[a]**	**-355.6±129.8**	-363.6±90.0	-367.5±107.4	-348.0±108.4
		PD	717.0±117.2	764.3±131.2	750.4±132.2	777.9±124.0	755.7±135.2	734.0±114.6
		Resultant	**890.8±141.3[a]**	**969.9±149.3[a]**	**955.9±172.0[a]**	983.6±144.3	956.8±158.3	930.4±139.8
	Torque (Nm)	AA	-84.33±24.71	-87.61±26.30	-85.35±34.24	-85.60±24.82	-89.76±28.22	-77.49±23.08
		IE	69.76±15.15	77.60±18.94	81.18±21.09	80.49±16.07	76.80±19.97	73.76±17.37
		HAA	77.62±20.11	80.93±20.14	78.45±22.80	83.61±20.22	79.21±20.98	80.03±18.58
		Resultant	135.4±30.2	143.7±32.4	144.0±37.5	146.2±26.5	143.5±35.5	135.2±27.1
Elbow	Force (N)	AP	271.6±51.5	284.5±68.7	289.3±83.9	283.4±69.6	285.1±69.4	276.4±65.6
		ML	249.1±55.7	267.9±51.6	273.3±58.0	272.2±40.3	268.0±56.8	252.1±50.0
		SI	633.4±109.5	673.5±89.0	667.2±108.8	674.3±79.4	668.0±101.6	656.1±86.4
		Resultant	735.1±119.6	781.6±103.4	781.0±124.3	783.2±90.9	777.3±115.6	757.8±101.5
	Torque (Nm)	VV	65.54±14.12	72.65±16.95	74.79±17.86	74.51±14.38	71.97±17.93	69.00±14.86
		EF	-52.51±10.08	-55.29±14.58	-56.74±18.27	-55.68±15.59	-55.15±14.47	-54.20±13.98
		Resultant	84.41±15.01	91.69±20.68	94.58±22.68	93.46±19.09	91.13±21.10	88.07±18.89

The ANOVA tests comparing low, medium, and high internal and external ROA groups, respectively, with kinetic variables had several statistically significant differences (Table 21). For the internal ROA comparisons, there were no statistically significant differences found. For the external ROA comparisons, there were seven statistically significant differences found in the superior/inferior shoulder force, abduction/adduction shoulder torque, internal/external rotation shoulder torque, resultant shoulder torque, medial/lateral elbow force, valgus/varus elbow torque, and resultant elbow torque.

Table 21: Comparing across mean ± standard deviation low, medium, and high groups for internal and external ROA, respectively. Where bold for $p < 0.05$ and statistically significant post-hoc tests a: Low vs. Medium, b: Low vs. High, and c: Medium vs. High.

			Internal ROA			External ROA		
			Low	Medium	High	Low	Medium	High
Shoulder	Force (N)	AP	-441.3±96.0	-446.9±103.2	-444.0±77.5	-477.2±100.0	-445.1±97.1	-419.4±94.3
		SI	-354.7±96.7	-364.3±103.3	-369.0±119.0	**-364.3±83.9**	**-375.2±110.6[c]**	**-317.1±83.3[c]**
		PD	755.2±116.6	756.5±137.2	754.3±113.8	797.6±117.3	751.0±138.9	738.3±95.1
		Resultant	950.7±136.9	958.8±159.6	956.2±143.7	1004.2±136.6	958.0±161.4	912.1±118.9
	Torque (Nm)	AA	-87.49±23.40	-86.92±26.34	-85.95±33.90	**-87.96±23.85**	**-90.13±28.39[c]**	**-73.37±20.00[c]**
		IE	72.53±12.96	77.46±19.69	79.42±20.59	**79.54±15.88[b]**	**78.45±20.49[c]**	**68.88±11.95[bc]**
		HAA	80.70±19.02	80.90±20.73	76.37±20.70	83.62±22.21	79.76±21.24	78.63±15.05
		Resultant	140.7±26.6	143.2±33.4	142.1±36.4	**147.0±27.4[b]**	**145.1±35.5[c]**	**129.0±20.6[bc]**
Elbow	Force (N)	AP	278.7±67.2	283.0±67.2	289.5±76.7	287.6±69.5	288.0±71.7	261.2±49.8
		ML	260.3±42.7	266.8±55.2	268.6±55.9	**270.5±37.1**	**271.6±57.3[c]**	**240.2±40.6[c]**
		SI	668.3±84.5	667.0±100.8	665.8±83.0	680.8±81.2	671.3±100.4	639.0±81.4
		Resultant	772.4±93.7	775.0±114.7	777.5±102.8	790.3±86.0	782.4±117.1	733.2±85.0
	Torque (Nm)	VV	68.47±11.68	72.40±17.78	73.52±17.34	**74.75±14.12[b]**	**73.23±18.24[c]**	**64.34±10.30[bc]**
		EF	-53.56±13.66	-55.18±14.60	-56.26±15.42	-57.58±16.44	-55.77±14.84	-50.24±10.21
		Resultant	87.45±15.18	91.43±21.34	93.09±20.95	**94.92±18.94[b]**	**92.47±21.78[c]**	**82.03±11.99[bc]**

The ANOVA tests comparing low, medium, and high internal and external SRF groups, respectively, with kinetic variables had several statistically significant differences (Table 22). For the internal SRF comparisons, there were six statistically significant differences found in the proximal/distal shoulder force, abduction/adduction shoulder torque, internal/external rotation shoulder torque, resultant shoulder torque, extension/flexion elbow torque, and resultant elbow torque. For the external SRF comparisons, there were four statistically significant differences found in the internal/external rotation shoulder torque, anterior/posterior elbow force, extension/flexion elbow torque, and resultant elbow torque.

Table 22: Comparing across mean ± standard deviation low, medium, and high groups for internal and external SRF, respectively. Where bold for $p < 0.05$ and statistically significant post-hoc tests a: Low vs. Medium, b: Low vs. High, and c: Medium vs. High.

			Internal SRF			External SRF		
			Low	Medium	High	Low	Medium	High
Shoulder	Force (N)	AP	-463.2±103.4	-444.1±98.0	-437.0±94.8	-449.3±79.8	-441.4±101.3	-459.8±96.9
		SI	-383.3±124.2	-361.4±103.0	-355.8±93.8	-330.0±80.5	-362.5±109.8	-391.5±90.5
		PD	**816.2±113.1**	**749.1±130.0**	**736.5±132.2**	744.9±86.7	756.9±142.3	759.8±100.4
		Resultant	1022.4±142.9	950.1±153.1	933.9±150.3	936.0±97.6	955.9±167.3	977.1±119.9
	Torque (Nm)	AA	**-100.6±32.9**[a]	**-84.80±25.07**[a]	**-84.85±28.29**	-78.79±19.02	-87.03±28.28	-92.07±26.12
		IE	**85.65±21.69**[a]	**74.78±17.18**[a]	**79.65±22.16**	**70.65±13.39**[b]	**76.35±18.43**	**84.00±22.41**[b]
		HAA	87.14±23.89	79.75±19.83	76.10±19.17	76.57±13.35	81.20±21.34	78.41±20.77
		Resultant	**160.2±38.4**[a]	**139.7±30.5**[a]	**140.7±34.2**	132.0±18.6	142.9±34.1	148.9±33.4
Elbow	Force (N)	AP	311.9±66.1	279.5±67.5	276.7±71.4	**269.7±50.4**[b]	**277.6±68.2**[c]	**316.8±72.5**[bc]
		ML	281.5±51.2	262.8±51.5	267.7±61.9	248.8±43.8	265.5±51.8	280.2±62.2
		SI	698.8±92.5	666.4±94.7	643.3±95.0	648.8±74.1	669.6±100.0	669.7±88.6
		Resultant	818.1±104.4	771.7±108.5	753.5±109.8	747.9±78.4	774.9±113.5	795.3±108.1
	Torque (Nm)	VV	79.49±18.31	70.43±15.58	72.41±19.87	65.97±11.34	71.71±16.66	77.11±19.56
		EF	**-62.04±14.82**[ab]	**-54.22±13.89**[a]	**-53.16±15.97**[b]	**-52.64±9.09**[bc]	**-53.96±14.56**[c]	**-61.54±16.12**[bc]
		Resultant	**101.18±21.94**[a]	**89.31±18.97**[a]	**90.40±23.29**	**84.81±11.73**[b]	**90.15±20.36**	**99.17±23.17**[b]

The primary differences among the low, medium, and high internal EPA groups appear in the proximal/distal and superior/inferior shoulder force (Figure 18). Plots of internal ROA and SRF produce similar findings. The figure shows the force and torque for the entire pitching motion with the time normalized from foot contact (FC: 0%) and ball release (BR: 100%). Many of the curves are very similar for all three groups with slight variations at both the peaks and valleys.

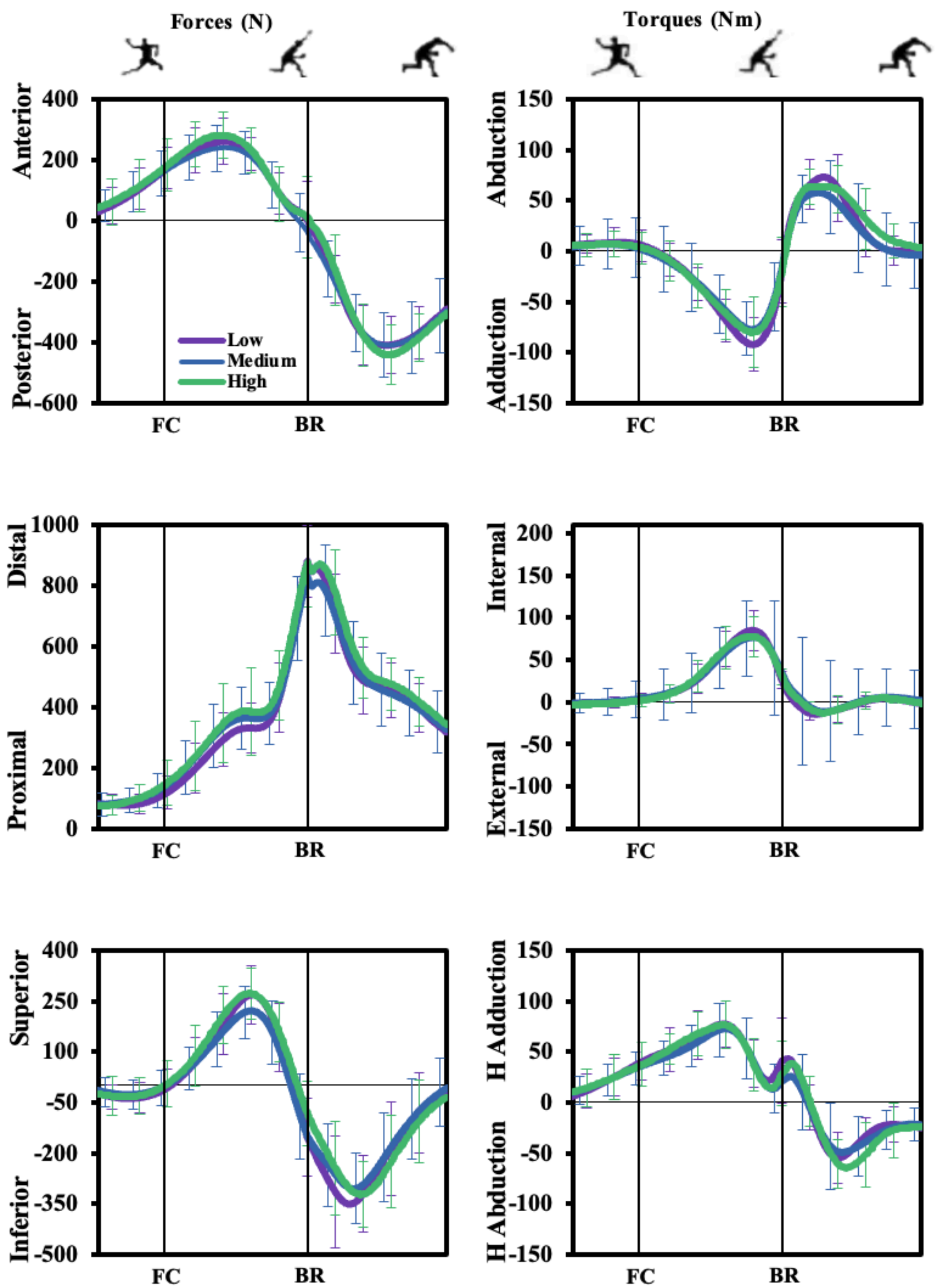

Figure 18: Shoulder forces and torques (mean ± standard deviation) for low, medium, and high internal EPA during baseball pitching. Time normalized from foot contact (FC: 0%) and ball release (BR: 100%).

The primary differences among the low, medium, and high external EPA groups appear in the internal/external rotation and horizontal adduction/abduction shoulder torques (Figure 19). Plots of external ROA and SRF produce similar findings. The figure shows the force and torque for the entire pitching motion with the time normalized from foot contact (FC: 0%) and ball release (BR: 100%). The external EPA groups have much more variation compared to the internal EPA groups. The variation being at the peaks and valleys, but also at other times throughout the pitching motion as well.

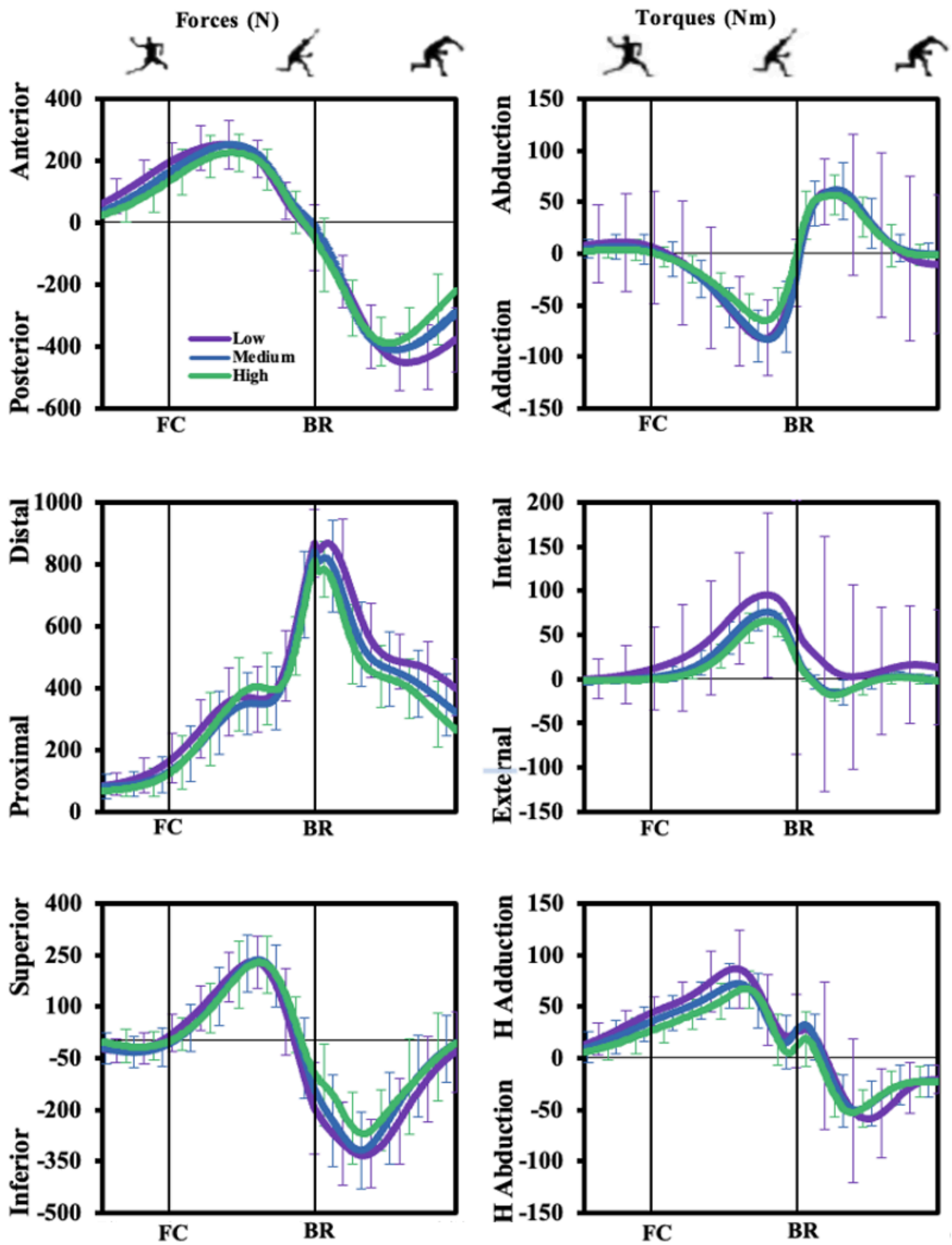

Figure 19: Shoulder forces and torques (mean ± standard deviation) for low, medium, and high external EPA during baseball pitching. Time normalized from foot contact (FC: 0%) and ball release (BR: 100%).

5.4. Objective 3 – Injury vs. Shoulder Exam

The objective 3 – injury vs. shoulder exam provides a detailed look at all shoulder exam variables with follow-up injury, injury history, no injury, and pitchers with both follow-up injury and injury history. The mean ± standard deviation and one-way ANOVA p-values calculated and reported. The comparison between dominant and non-dominant arm for all injury groups for the shoulder exam variables were displayed in bar graphs. This section continues the investigation of the three pillars in baseball pitching.

There were relationships between the shoulder exam variables and injury variables (Table 23). There was one statistically significant relationship between the dominant throwing arm internal SRF and the injury variables, where both follow-up injury and injury history group had the largest SRF and the no injury group had the smallest SRF ($p = 0.026$, with no statistically significant post-hoc tests). There were some variations among the other groups but no statistically significant differences.

Table 23: The mean ± standard deviation of the shoulder exam variables for follow-up injury, injury history, no injury, and follow-up injury and injury history, where $p < 0.05$ is bolded.

			Follow-up Injury	Injury History	No Injury	Follow-up Injury and Injury History	p
Dominant	Internal	EPA (deg)	73.35±11.45	73.11±13.05	72.06±13.50	79.71±8.54	0.445
		ROA (deg)	36.80±13.97	42.23±14.77	40.99±15.09	40.08±13.46	0.536
		SRF (deg/Nm)	**3.37±0.68**	**3.04±0.94**	**2.98±0.72**	**3.61±0.41**	**0.026**
	External	EPA (deg)	139.4±10.9	137.1±11.4	137.2±11.3	140.3±10.7	0.722
		ROA (deg)	106.3±12.9	107.4±12.9	105.3±12.7	112.1±11.2	0.463
		SRF (deg/Nm)	4.66±1.72	3.99±1.84	4.37±1.68	3.69±0.99	0.304
		Total ROM (deg)	212.7±13.5	210.2±18.7	209.2±16.7	220.0±15.8	0.305
		SEIR	1.96±0.44	1.93±0.40	1.98±0.44	1.77±0.20	0.617
Non-dominant	Internal	EPA (deg)	84.74±14.20	83.45±13.81	84.23±12.02	83.09±11.64	0.974
		ROA (deg)	53.32±16.46	56.31±13.81	52.04±13.44	53.52±12.27	0.455
		SRF (deg/Nm)	3.22±1.15	2.95±0.91	3.22±0.85	2.82±0.63	0.287
	External	EPA (deg)	129.8±11.0	130.3±13.5	128.7±14.0	131.1±12.8	0.904
		ROA (deg)	95.04±12.28	97.80±13.47	96.61±12.40	97.77±15.85	0.858
		SRF (deg/Nm)	4.88±1.01	4.48±1.62	4.43±1.56	4.16±1.43	0.529
		Total ROM (deg)	214.5±14.7	213.8±16.8	213.0±17.0	214.2±18.9	0.975
		SEIR	1.58±0.31	1.61±0.34	1.56±0.29	1.60±0.23	0.871
Bilateral Difference		Internal EPA (deg)	-11.39±13.41	-10.33±13.21	-12.17±11.34	-3.38±10.97	0.240
		Total ROM (deg)	-1.79±12.07	-3.59±15.54	-3.75±14.51	5.78±16.78	0.331

The bar graphs show the variation in dominant and non-dominant arm for each injury group (Figure 20). The internal and external shoulder exam variables have very inverted relationships for both the EPA and ROA the dominant arm has much less internal rotation but much greater external rotation when compared to the non-dominant arm and for the SRF the dominant arm has generally greater internal flexibility but less external flexibility when compared to the non-dominant arm, excluding the no injury group. Comparing the dominant and non-dominant arm for each injury group there were many statistically significant differences. For the internal EPA the follow-up injury, injury history, and no injury group all had statistically significant differences between the dominant and non-dominant arms. For the internal ROA the follow-up injury, injury history, no injury, and follow-up injury and injury history group all had statistically significant differences between the dominant and non-dominant arms. For the internal SRF the no injury and follow-up injury and injury history group had statistically significant differences between the dominant and non-dominant arms. For the external EPA the follow-up injury, injury history, and no injury group all had statistically significant differences between the dominant and non-dominant arms. For the external ROA the follow-up injury, injury history, no injury, and follow-up injury and injury history group all had statistically significant differences between the dominant and non-dominant arms. For the external SRF there were no statistically significant differences between the dominant and non-dominant arms.

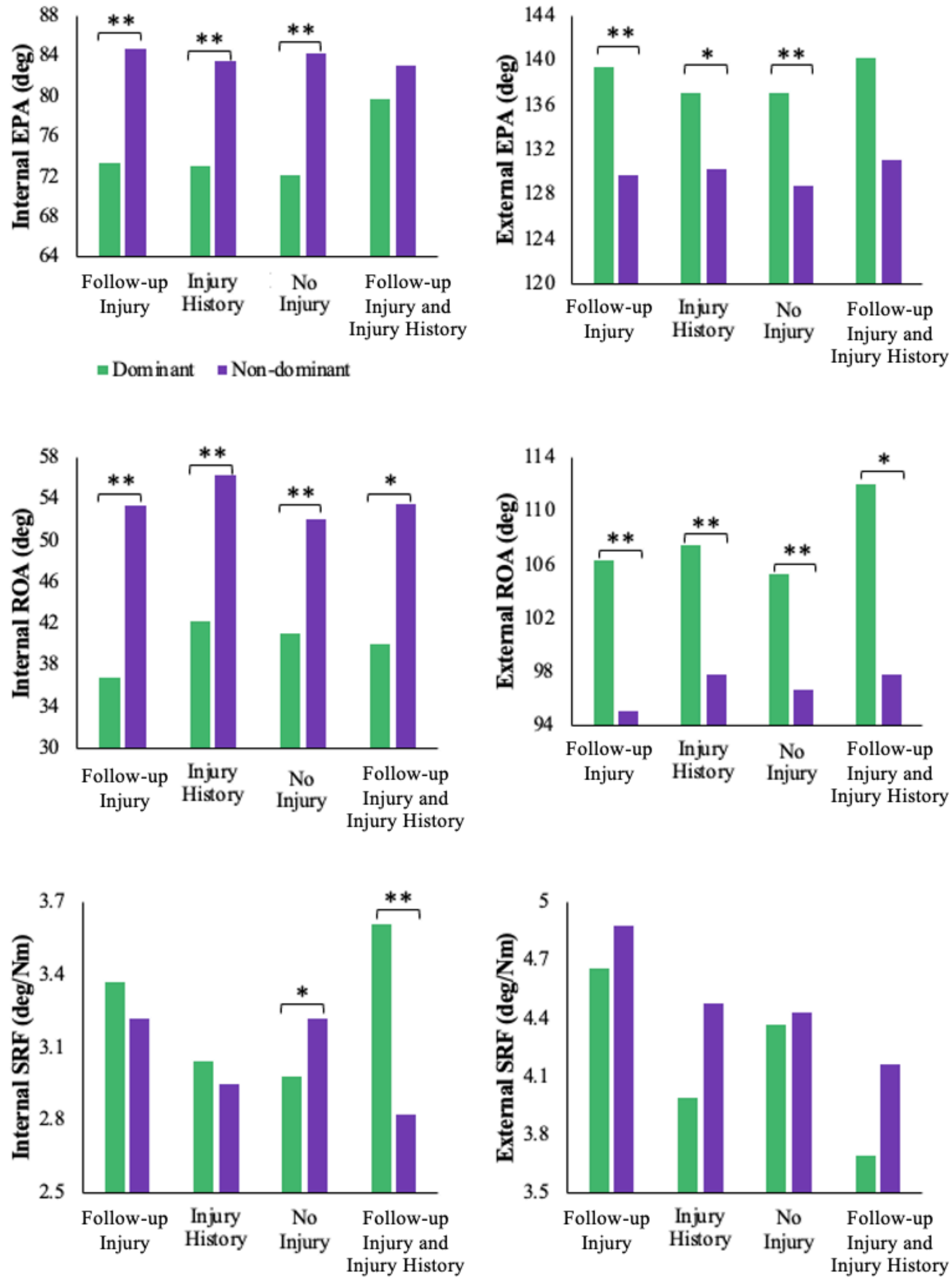

Figure 20: Internal and external EPA, ROA, and SRF for both arms for all injury groups, where comparing dominant and non-dominant arms * means $p < 0.05$ and ** means $p < 0.01$.

5.5. Objective 4 – Biomechanics vs. Injury

The objective 4 – biomechanics vs. injury provides a detailed look at kinematics vs. injury and kinetics vs. injury. The mean ± standard deviation and one-way ANOVA p-values are calculated and reported. The comparison between the no injury, shoulder follow-up injury, elbow follow-up injury, and both the shoulder and elbow follow-up injury groups and shoulder kinetic variables throughout the pitching cycle were displayed in plots. This section concludes the investigation of the three pillars in baseball pitching.

5.5.1. Kinematics vs. Injury

There were relationships between the kinematic variables and injury variables (Table 24). There was one statistically significant relationship between the shoulder horizontal adduction angle and the injury variables, where the no injury group had the largest shoulder horizontal adduction angle and both follow-up injury and injury history group had the smallest SRF ($p = 0.045$, with no statistically significant post-hoc tests). There were some variations among the other groups but no statistically significant differences.

Table 24: The mean ± standard deviation of the peak biomechanics variables (kinematics) for follow-up injury, injury history, no injury, and follow-up injury and injury history, where $p < 0.05$ is bolded.

	Follow-up Injury	Injury History	No Injury	Follow-up Injury and Injury History	p
Ball Speed (mph)	78.87±4.85	77.21±4.64	77.46±4.66	78.13±4.04	0.517
Stride Length (m)	0.69±0.05	0.69±0.04	0.68±0.05	0.70±0.05	0.193
Lead Foot Angle (deg)	-16.25±10.83	-13.78±15.11	-17.84±15.09	-16.32±11.27	0.522
Knee Angle at Foot Contact (deg)	139.7±7.2	137.9±8.3	138.3±10.5	135.4±5.2	0.700
Knee Angle at Ball Release (deg)	146.5±14.1	144.9±15.7	146.8±13.1	138.4±11.0	0.377
Elbow Angle at Foot Contact (deg)	104.5±18.5	94.5±19.0	100.1±18.5	107.8±20.4	0.109
Initial Elbow Extension Angle (deg)	85.30±13.49	82.54±15.99	84.69±13.64	87.93±9.01	0.723
Elbow Angle at Ball Release (deg)	149.8±6.6	152.6±8.1	152.2±6.5	151.2±7.5	0.419
Forward Trunk Angle (deg)	28.97±9.73	25.09±11.32	28.38±7.57	28.09±9.18	0.222
Lateral Trunk Angle (deg)	19.09±7.94	22.33±10.36	21.33±9.34	22.30±10.08	0.591
Shoulder Abduction Angle (deg)	96.62±8.73	94.96±8.78	94.55±8.36	90.52±12.00	0.373
Shoulder Horizontal Adduction Angle (deg)	**23.90±7.30**	**20.69±7.54**	**23.95±7.78**	**18.59±6.08**	**0.045**
Maximum External Rotation Angle (deg)	175.5±13.1	171.6±11.7	174.7±10.9	175.5±10.2	0.464
Spine Lateral Bend Angle (deg)	0.93±6.30	2.33±7.08	1.75±7.49	-1.02±5.42	0.633
Maximum Hip Angular Velocity (deg/s)	542.1±84.2	543.1±89.1	532.5±81.0	549.4±66.5	0.851
Maximum Trunk Angular Velocity (deg/s)	310.4±54.3	314.9±55.6	306.7±54.2	296.1±77.4	0.792

Maximum Elbow Angular Velocity (deg/s)	2257±216	2259±308	2249±282	2180±193	0.901
Maximum Shoulder Internal Rotation Angular Velocity (deg/s)	7482±1387	7624±1970	7467±1512	6937±1125	0.742
Maximum Shoulder Horizontal Adduction Angular Velocity (deg/s)	1051±200	997±235	999±204	911±233	0.414
Maximum Spine Axial Rotation Angular Velocity (deg/s)	502.2±95.3	501.5±130.5	509.8±118.4	523.4±79.1	0.952
Maximum Spine Lateral Bend Angular Velocity (deg/s)	290.8±57.9	315.4±72.1	299.1±64.2	300.9±48.6	0.461
Maximum Hip Linear Velocity (m/s)	1.91±0.32	1.94±0.35	1.81±0.35	1.96±0.29	0.184
Maximum Shoulder Linear Velocity (m/s)	3.61±0.45	3.60±0.40	3.57±0.44	3.76±0.38	0.668

5.5.2. Kinetics vs. Injury

There were relationships between the kinetic variables and injury variables (Table 25). There were no statistically significant findings between the kinetic variables and the injury variables. The no injury group was often in between the three different injury groups with the injury groups more extreme. There were some variations among the other groups but no statistically significant differences.

Table 25: The mean ± standard deviation of the peak biomechanics variables (kinetics) for follow-up injury, injury history, no injury, and follow-up injury and injury history, where $p < 0.05$ is bolded and asterisk (*) indicates a statistically significant post-hoc test.

	Follow-up Injury	Injury History	No Injury	Follow-up Injury and Injury History	p
AP Shoulder Force (N)	-455.9±113.5	-458.6±82.2	-443.0±101.5	-383.1±30.3	0.234
SI Shoulder Force (N)	-341.8±69.4	-376.9±102.1	-360.6±109.2	-403.7±136.9	0.398
PD Shoulder Force (N)	778.5±137.1	750.2±124.2	757.8±127.6	687.6±161.4	0.384
Resultant Shoulder Force (N)	969.5±163.8	964.2±133.3	956.5±154.9	889.9±187.0	0.619
AA Shoulder Torque (Nm)	-85.31±21.92	-83.99±26.43	-88.26±28.54	-86.88±27.61	0.854
IE Shoulder Torque (Nm)	71.61±12.54	77.96±19.17	77.36±20.18	83.08±15.30	0.394
HAA Shoulder Torque (Nm)	81.54±21.01	77.65±18.63	80.91±20.70	77.71±25.13	0.816
Resultant Shoulder Torque (Nm)	139.3±26.6	139.9±31.4	144.1±34.6	144.7±33.5	0.859
AP Elbow Force (N)	273.5±55.2	289.2±73.3	283.2±69.3	286.9±79.2	0.849
ML Elbow Force (N)	265.7±41.8	271.7±52.1	264.8±57.1	254.4±38.2	0.837
SI Elbow Force (N)	692.4±103.0	680.0±78.6	660.2±98.8	618.0±73.4	0.161
Resultant Elbow Force (N)	792.6±108.8	790.6±94.4	768.6±115.0	730.5±88.1	0.376
VV Elbow Torque (Nm)	67.78±11.63	74.64±17.69	71.89±17.88	72.09±10.08	0.476
EF Elbow Torque (Nm)	-52.28±12.18	-56.44±15.82	-55.29±14.60	-54.54±15.08	0.733
Resultant Elbow Torque (Nm)	85.98±14.65	94.11±21.47	91.12±21.33	90.75±16.03	0.494

There were variations among the shoulder forces and torques for all follow-up injury (no injury, shoulder injury, elbow injury, and both shoulder and elbow injury) groups (Figure 21). There were clear variations in the proximal/distal shoulder force with the no injury group falling right in between the shoulder follow-up injury group and the elbow follow-up injury group. The same pattern was also found in the horizontal adduction/abduction torque. It is important to note the variation in both (shoulder and elbow) follow-up injury group is because only there are only four pitchers.

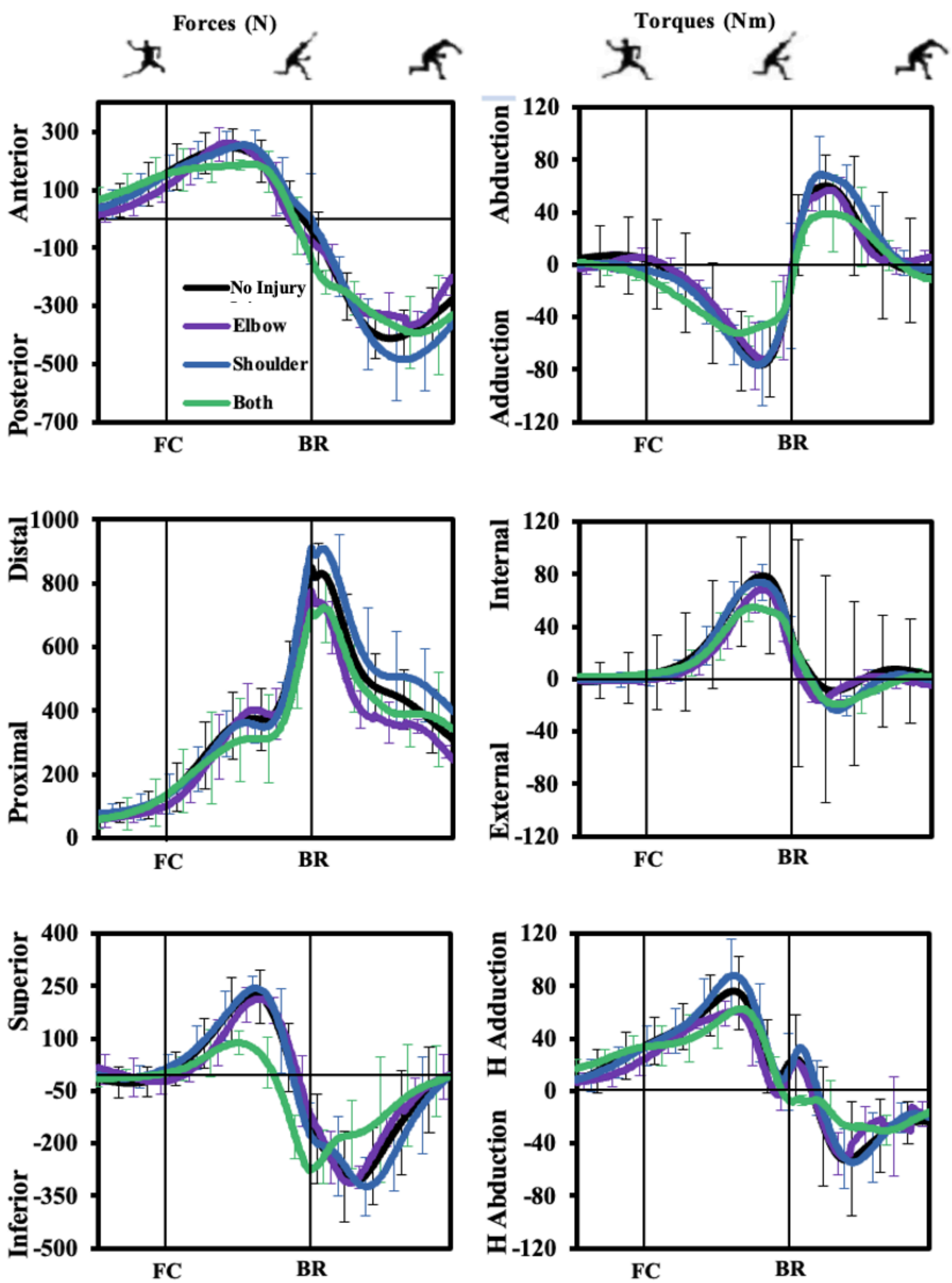

Figure 21: Shoulder forces and torques (mean ± standard deviation) for no injury, elbow follow-up injury, shoulder follow-up injury, and both (shoulder and elbow) follow-up injury during baseball pitching. Time normalized from foot contact (FC: 0%) and ball release (BR: 100%).

5.6. Objective 5 – Throwing Biomechanics Index for Baseball Pitching

The objective 5 – throwing biomechanics index for baseball pitching provides a detailed look into all the biomechanical variables discussed and how they are interrelated. The outputs will help connect the factors that impact performance (defined by ball speed) and injury. This section serves as a connecting point to summarize all the variables of this study.

5.6.1. Throwing Biomechanics Index Defined

The results show the no injury and high performing group had the highest throwing biomechanics index compared to the other groups (Figure 23). The injury history group's throwing biomechanics index is 7.19 ± 1.75, the follow-up injury group's throwing biomechanics index is 7.59 ± 1.31, the injury history and follow-up injury group is 7.57 ± 1.24, and the no injury and high performing group was 7.69 ± 1.67, when comparing across the three injury groups and the no injury and high performing group's index score there was no statistically significant difference.

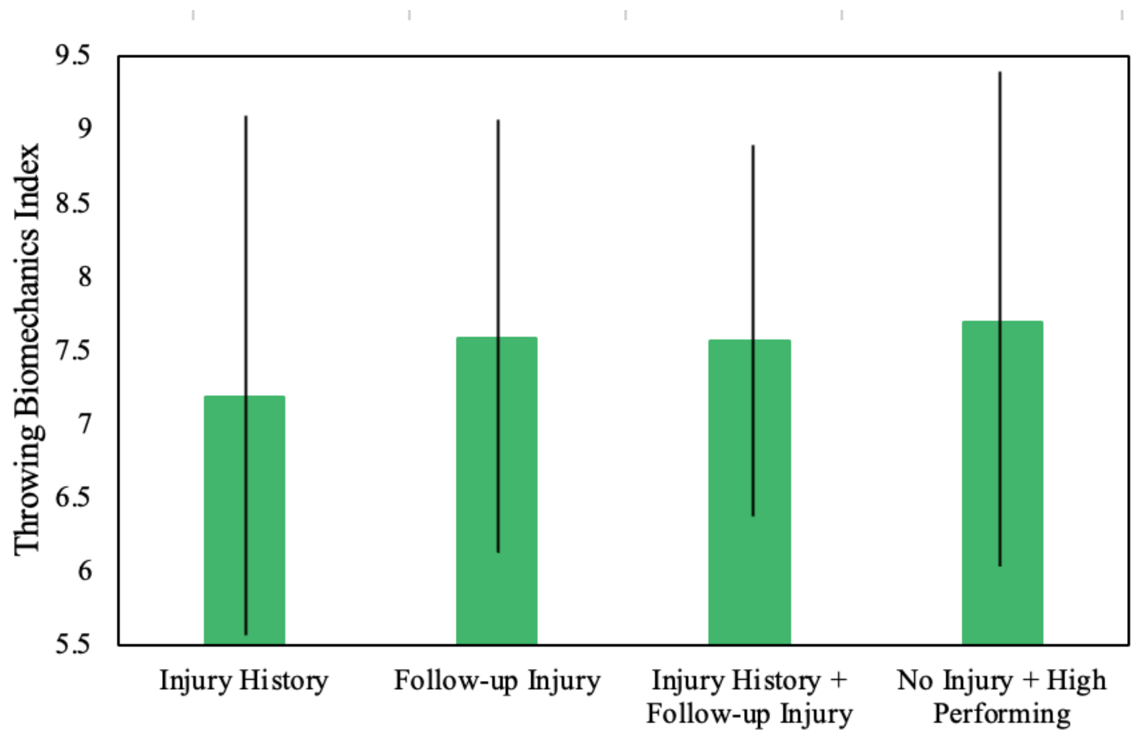

Figure 22: The throwing biomechanics index for the injury history, follow-up injury, injury history and follow-up injury, and the no injury and high performing groups.

Further analysis investigated the individual index scores for all fifteen variables that were used to create the index (Table 26). When comparing across the three injury groups and the no injury and high performing group's index score for each of the fifteen variables there was no statistically significant difference. The no injury and high performing group has the largest mean for six of the fifteen variables.

Table 26: The mean and standard deviation for the individual index scores (maximum of 1) for all fifteen variables that were used to create the index for the injury history, follow-up injury, and injury history and follow-up injury groups and the no injury and high performing group.

	Injury History	Follow-up Injury	Injury History + Follow-up Injury	No Injury + High Performing	p
Stride Length at Foot Contact	0.49±0.30	0.40±0.32	0.28±0.22	0.52±0.27	0.187
Foot Angle	0.45±0.36	0.42±0.28	0.42±0.29	0.47±0.30	0.862
Knee Angle at Foot Contact	0.58±0.29	0.58±0.23	0.68±0.22	0.47±0.27	0.166
Max Hip Angular Velocity	0.47±0.30	0.57±0.34	0.59±0.32	0.62±0.29	0.254
Trunk Forward Angle	0.39±0.30	0.43±0.26	0.45±0.34	0.50±0.27	0.439
Max Spine Lateral Bend Angular Velocity	0.47±0.31	0.52±0.31	0.58±0.33	0.50±0.30	0.884
Max External Rotation Angle	0.44±0.33	0.44±0.32	0.44±0.26	0.52±0.27	0.660
Elbow Angle at Foot Contact	0.40±0.26	0.50±0.29	0.25±0.19	0.46±0.26	0.137
Max Elbow Angular Velocity	0.41±0.32	0.51±0.28	0.40±0.25	0.55±0.28	0.317
Anterior/Posterior Shoulder Force	0.43±0.26	0.44±0.31	0.68±0.11	0.50±0.31	0.104
Superior/Inferior Shoulder Force	0.54±0.27	0.61±0.17	0.47±0.29	0.51±0.29	0.351
Proximal/Distal Shoulder Force	0.57±0.29	0.49±0.27	0.72±0.32	0.51±0.29	0.269
Internal/External Shoulder Torque	0.55±0.28	0.61±0.20	0.43±0.26	0.52±0.28	0.261
Resultant Elbow Force	0.49±0.25	0.46±0.25	0.65±0.23	0.50±0.31	0.433
Valgus/Varus Elbow Torque	0.52±0.28	0.59±0.21	0.52±0.21	0.52±0.28	0.527
Total Index Value	7.19±1.75	7.59±1.31	7.57±1.24	7.69±1.67	0.578

5.6.2. Throwing Biomechanics Index Compared with Demographics and Performance

The results show that many of the pitcher demographic variables are related to the throwing biomechanics index (Table 27). The height, mass, age, and forearm length all have a moderately strong negative statistically significant correlation with the throwing biomechanics index. Showing that the larger throwing biomechanics index was related to smaller demographic variables and the smaller throwing biomechanics index was related to the larger demographic variables. The other three demographic variables of BMI, upper arm length, and years played did not have any statistical significance with the throwing biomechanics index.

Table 27: The Pearson correlation values for the pitcher demographic variables and the throwing biomechanics index, where $p < 0.05$ is bolded.

	R	p
Height	**-0.2368**	**0.0165**
Mass	**-0.3490**	**0.0003**
BMI	-0.1604	0.1073
Age	**-0.2542**	**0.0099**
Forearm Length	**-0.3747**	**0.0001**
Upper Arm Length	-0.0148	0.8826
Years Played	-0.1024	0.3058

The results show that the throwing biomechanics index was not statistically correlated with the ball speed (Table 28). The Pearson correlation value for ball speed and throwing biomechanics index was -0.1496 meaning that the larger throwing biomechanics index was related to lower ball speed and the smaller throwing biomechanics index was related to the higher ball speed; however, there was no statistical significance.

Table 28: The Pearson correlation values for the pitcher performance (defined as ball speed) and the throwing biomechanics index, where $p < 0.05$ is bolded.

	R	p
Ball speed	-0.1496	0.1334

5.6.3. Throwing Biomechanics Index Compared with Shoulder Exam

The results show that many of the pitcher shoulder exam variables are related to the throwing biomechanics index (Table 29). The dominant arm internal SRF, dominant arm external ROA, and non-dominant arm external ROA all have a moderately strong positive statistically significant correlation with the throwing biomechanics index. Showing that the smaller throwing biomechanics index was related to smaller shoulder exam variables and the larger throwing biomechanics index was related to the larger shoulder exam variables. The dominant arm external SRF has a moderately strong negative statistically significant correlation with the throwing biomechanics index. Showing that the larger throwing biomechanics index was related to smaller dominant arm external SRF and the smaller throwing biomechanics index was related to the larger dominant arm external SRF. The other shoulder exam variables had various trends but did not have any statistical significance with the throwing biomechanics index.

Table 29: The Pearson correlation values for the pitcher shoulder exam variables (including dominant, non-dominant, and bilateral difference variables) and the throwing biomechanics index, where $p < 0.05$ is bolded.

			R	p
Dominant	Internal	EPA	-0.0806	0.4206
		ROA	-0.1627	0.1023
		SRF	**0.3105**	**0.0015**
	External	EPA	0.1618	0.1042
		ROA	**0.3642**	**0.0002**
		SRF	**-0.2422**	**0.0142**
		Total ROM	0.0463	0.6440
		SEIR	0.1738	0.0806
Non-dominant	Internal	EPA	-0.0197	0.8442
		ROA	-0.0768	0.4430
		SRF	0.1322	0.1853
	External	EPA	0.1870	0.0598
		ROA	**0.2113**	**0.0330**
		SRF	0.1733	0.0815
		Total ROM	0.1250	0.2106
		SEIR	0.1310	0.1894
Bilateral Difference		Internal EPA	-0.0598	0.5505
		Total ROM	-0.0978	0.3281

CHAPTER 6: DISCUSSION

The discussion chapter covers the summary of variables, objective 1 – demographics vs. shoulder exam, biomechanics, and injury, objective 2 – shoulder exam vs. biomechanics, objective 3 – injury vs. shoulder exam, objective 4 – biomechanics vs. injury, and objective 5 – baseball pitching regression modeling. This chapter dives into the findings of this study and how it is related to current literature.

6.1. Objective 1 – Demographics vs. Shoulder Exam, Biomechanics, and Injury

The first null hypothesis was rejected because there were strong relationships between the demographic variables with the shoulder exam, baseball pitching biomechanics, and throwing arm injury variables. The strongest relationships between the demographic variables and shoulder exam variables were between the dominant arm internal EPA and division level and the dominant arm internal SRF and forearm length. The strongest relationships between demographic variables and kinematic variables were between the ball speed and forearm length and the maximum external rotation angle and age. The strongest relationships between the demographic variables and kinetic variables were the elbow SI force and mass and the shoulder SI force and mass. The strongest relationships between demographic variables and the injury variables were in division and follow-up years. There has been very minimal analysis of pitcher demographics with any variables including shoulder exam, biomechanics, or injury, so this analysis leads to the beginning of new understandings.

The demographic variables are important to consider because throughout development of the pitcher they vary greatly as the pitcher's grow. Identifying connections with demographic variables and shoulder exam, biomechanics, and injury variables could give key insights on proper development and training protocols for all ages. Further investigations of the demographic variables and kinetic variables, the mass of the athlete impacting the elbow and shoulder SI force follows general logic of the larger athlete producing more loading. Analysis looking at the demographics and biomechanics could help a large range of athletes to be able to gain greater understanding for optimal mechanics to reduce injury and improve performance.

There are often tons of epidemiology's at all levels from youth to collegiate to major league baseball, but often times they don't discuss demographic variables and how these variables may be impacting injury (Boltz et al., 2021; Ciccotti et al., 2017; DeFroda et al., 2018; Dick et al., 2007; Posner et al., 2011; Saper et al., 2018; Wasserman et al., 2019). The previous work gives information and trends of injury but does not clearly identify potential mechanisms so additional future work would be advantageous for deeper understanding.

The demographic variables that were most closely related to the shoulder exam variables were the division level and forearm length. The division level may be because frequency of play or the available treatment may be higher at the higher division level, and this could impact the health of the shoulder. The forearm length follows as it impacts the motion of the upper arm as a whole and could play a role in the shoulder health and shoulder exam variables. Many studies have investigated the health of the shoulder in many different populations (Baker Jr & Merkley, 2000; Flores et al., 2020; Genovese, 2022; Polguj et al., 2011; Zaid et al., 2019). Looking deeper with medical images or underlying conditions could help connect the demographic variables with the shoulder exam variables in a clear way.

6.2. Objective 2 – Shoulder Exam vs. Biomechanics

The second null hypothesis was rejected because there were strong relationships between the shoulder exam variables and baseball pitching biomechanics variables. The strongest relationships between dominant shoulder exam variables and kinematic variables were between maximum external rotation angle and external EPA and shoulder abduction angle and external EPA. The strongest relationships between the bilateral shoulder exam variables and kinematic variables were between maximum shoulder internal rotation angular velocity and bilateral difference internal EPA and maximum shoulder horizontal adduction angle and bilateral difference total ROM. The strongest relationships between dominant shoulder exam variables and kinetic variables were between elbow AP force and external SRF and shoulder IE torque and external ROA. The strongest relationships between the bilateral shoulder exam variables and kinetic variables were between elbow AP force and bilateral difference total ROM.

Diving further into the comparisons of EPA, ROA, and SRF and kinematic variables there were many relationships found. The internal EPA found differences with the lead foot angle and the knee angle at ball release, where external EPA found differences with elbow angle at ball release, shoulder abduction angle, maximum external rotation angle, and maximum shoulder linear velocity. The internal ROA found differences with the ball speed and knee angle at ball release, where external ROA found differences with the stride length, elbow angle at ball release, shoulder abduction angle, and maximum external rotation angle. The internal SRF found differences with the maximum shoulder horizontal adduction angular velocity and maximum hip linear velocity, where external SRF found differences with the knee angle at foot contact and forward trunk angle.

Diving further into the comparisons of EPA, ROA, and SRF and kinetic variables there were many relationships found. The internal EPA found differences with superior/inferior shoulder force and resultant shoulder force, where external EPA there were no statistically significant differences found. The internal ROA found no statistically significant difference, where external ROA found differences with superior/inferior shoulder force, abduction/adduction shoulder torque, internal/external rotation shoulder torque, resultant shoulder torque, medial/lateral elbow force, valgus/varus elbow torque, and resultant elbow torque. The internal SRF found differences with proximal/distal shoulder force, abduction/adduction shoulder torque, internal/external rotation shoulder torque, resultant shoulder torque, extension/flexion elbow torque, and resultant elbow torque, where external SRF found differences with internal/external rotation shoulder torque, anterior/posterior elbow force, extension/flexion elbow torque, and resultant elbow torque. The primary differences seen in the plots for internal EPA was in the proximal/distal and superior/inferior shoulder forces and for external EPA was in the internal/external rotation and horizontal adduction/abduction shoulder torques.

Shoulder external exam variables recorded during a physical examination were associated with shoulder joint loading during baseball pitching. The Pearson correlation values were relatively small because of the large variance, but many statistically significant correlations were found. Loss of shoulder ROM showed an increase in shoulder joint loading. These findings show that shoulder external exam variables are related to shoulder joint loading during baseball pitching, aligning with previous work (Bullock et al., 2018; Fleisig et al., 1995; Takagi et al., 2014). The differences for the peak values could be contributed to different pitching styles or mechanics, like previous studies (Sabick et al., 2005; Urbin et al., 2013). Quantifying shoulder external exam variables and comparing them with shoulder joint loading during baseball pitching is novel and helps us understand the injury mechanisms.

There is great emphasis on the importance of investigating baseball pitching with shoulder physical exam measurements. The most common measurements to quantify shoulder health are GIRD and TRMD, which were very similar measures to our bilateral difference internal EPA and bilateral difference total ROM. Where GIRD focuses only on internal rotation and TRMD on both internal and external rotation, and both found no differences between any pitching kinematics nor kinetics. Our findings are pointing to the value in the SEIR measurement because it emphasizes the external rotation and its relationship with the internal rotation. Gaining external rotation is important for proper pitching mechanics it is imperative to keeping pitchers healthy and improving performance. The loss of external rotation leads to abnormal joint motions and loadings. Further, SEIR highlights the external rotation over internal rotation focusing on one arm at a time. The SEIR value was significantly larger on the throwing arm in comparison to the non-throwing arm and this is most likely due to the demand of the pitching motion and retroversion (Greenberg et al., 2017). The focus being on the throwing arm shoulder and its relationship to baseball pitching biomechanics opposed to also looking at the non-throwing arm because this is also where the injuries occur for all throwing athletes (Dick et al., 2007; Hibberd et al., 2018; Kalo et al., 2020). Further investigations of the throwing arm shoulder exam with biomechanics and injury would be advantageous for all sports.

The lower SEIR group had the highest shoulder external rotation angle at foot contact (with no statistically significant correlation), but the lowest shoulder external rotation angle at maximum external rotation (statistically significant correlation, $p=0.009$), which led to smaller shoulder external rotation during arm cocking phase. Emphasizing that SEIR may be more related to the shoulder external rotation angle at maximum external rotation than the shoulder external rotation angle at foot contact. A smaller shoulder external rotation angle at maximum external rotation will lead to less time to accelerate and demand higher internal rotation velocity, which in turn could lead to higher varus torque at the elbow, which were consistent with our findings. The low SEIR group had the lowest shoulder horizontal adduction angle at foot contact but the largest shoulder horizontal adduction angle at the maximum external rotation. The higher horizontal adduction angular velocity is associated with higher ball velocity (Oyama, 2012). This demand on the shoulder results in the low SEIR group of having the largest horizontal adduction torque, compared to other groups. SEIR is highly related to all the variables and interconnected to pitching mechanics.

These findings emphasize that there are many factors that influence proper biomechanics. This aligns with previous studies, that concludes that the range of motion, velocity, fatigue, type of pitch, and pitching mechanics can all be an influential factors on performance (A. Popchak et al., 2015; Tyler et al., 2014). The orientation of the throwing-arm joint loading for both the shoulder and elbow joint also contributes to both the pitch delivery and possibly mechanisms of injury. There are many factors that relate to joint loading during throwing, which explains why even the statistically significant correlations between the shoulder exam variables and joint loading had moderately low R values. However, 10 to 15% changes in shoulder exam variables or pitching biomechanics variables may become the causes of potential injuries. The relationship between the shoulder exam variables and injury in collegiate baseball pitchers will be investigated in the future. The understanding of both the baseball pitching biomechanics and the physical exam that monitors shoulder health condition is advantageous.

In addition to the multitude of shoulder exam variables we quantified other studies used additional measurements to quantify shoulder health that include elbow valgus laxity, horizonal adduction, humeral retroversion, and many other (Greenberg et al., 2017; Laudner et al., 2020; Yasui et al., 2012). Investigating more variables could help understand the mechanism of injury. Another factor to consider is how the pitch count or pitching in general impacts the shoulder exam variables. A study showed that passive range of motion is statistically significantly decreased immediately after baseball pitching in professional pitchers (Reinold et al., 2008). The monitoring of these shoulder exam variables could not only help predict performance but also help identify potential injuries. This is important to note as longer studies are performed to investigate what is this connection between injury and performance and how they are related would be exciting future work to gain new understanding.

6.3. Objective 3 – Injury vs. Shoulder Exam

The third null hypothesis was rejected because there were strong relationships between the throwing arm injury variables and the shoulder exam variables. There was one statistically significant relationship between the dominant throwing arm internal SRF and the injury variables. There were some variations among the other groups but no statistically significant differences.

Diving further into the variation in dominant and non-dominant arm for each injury group there were many relationships found. The dominant and non-dominant arms for internal EPA found differences in the follow-up injury, injury history, and no injury group, where external EPA found differences in the follow-up injury, injury history, and no injury group. The dominant and non-dominant arms for internal ROA found differences in the follow-up injury, injury history, no injury, and follow-up injury and injury history group, where external ROA found differences in the follow-up injury, injury history, no injury, and follow-up injury and injury history group. The dominant and non-dominant arms for internal SRF found differences in the no injury and follow-up injury and injury history group, where external SRF found no statistically significant differences.

The evaluation of the shoulder is an important topic to help improve performance and reduce injuries. Previous studies found that the larger bilateral differences lead to shoulder tightness and increased risk for higher joint loadings (Laudner et al., 2012; Laudner et al., 2021). Another study reported a new way to assess elbow valgus laxity that uses a custom arm holder and validated using ultrasound (Yasui et al., 2012). Investigating shoulder exam variables may enable further understanding of the shoulder's health condition and their relationships to baseball pitching mechanics. One of the greatest values in quantifying the shoulder health condition is increasing the repeatability and comparison overtime. The use of the custom device to measure both the internal rotation and external rotation improves how the shoulders end range of motion is defined. Further, the custom device used in this study quantified additionally the stiffness and flexibility, which could give additional findings. This encourages the continual use and investigation of all the shoulder exam variables in additional to the new variable of SEIR and any other quantitative measurements to monitor shoulder health.

Wilk et al investigated the relationship of GIRD and TRMD with shoulder injuries in professional baseball pitching and found that they both lead to an increase in risk but only TRMD had a statistically significant relationship with shoulder injuries (Wilk et al., 2011). Further, the study found there was differing results between the major and minor league athletes with the minor league pitchers more likely to get injured but major league pitchers missing a greater number of games (Wilk et al., 2011). Our findings differ slightly from literature as we found that GIRD increases the likelihood of injury, but that TRMD reduced the likelihood of injury. These differences could be because of the difference in procedures of measuring the internal rotation and external rotation as well as the difference in level (college vs. professional). Additionally, with GIRD and TRMD the throwing arm is compared to the non-throwing arm which could be leading to varying results. The variability of the non-throwing arm range of motion could be a confounding variable and is eliminated by using the SEIR method. There is great value in understanding the relationships of all shoulder exam variables with throwing arm injuries in collegiate baseball pitchers.

Many other studies have investigated the impacts of shoulder exam variables on injury. Previous studies investigated both the throwing and non-throwing shoulder and how the shoulder exam variables may impact injury (Borsa et al., 2006; Garrison et al., 2012; Keller et al., 2018; Scher et al., 2010). There are mixed findings of some showing differences from the throwing arm to non-throwing arm, with the consensus being that shoulder exam variables can be predictive of throwing arm injuries, but the findings are not always statistically significant. Future quantitative physical examinations of throwing athletes that also track injuries may lead to a large database which could be very useful. This database may be analyzed using machine learning and lead to new knowledge, which would give great insight on the relationship of throwing sports and injury mechanisms.

6.4. Objective 4 – Biomechanics vs. Injury

The fourth null hypothesis was rejected because there were strong relationships between baseball pitching biomechanics variables and throwing arm injury variables. For the kinematic variables, there was one statistically significant relationship between the shoulder horizontal adduction angle and the injury variables. There were some variations among the other groups but no statistically significant differences. For the kinetic variables, there were no statistically significant differences with the injury variables. Further looking at the plots between the shoulder forces and torques for all follow-up injury (no injury, shoulder injury, elbow injury, and both shoulder and elbow injury) groups there were clear differences. The proximal/distal shoulder force and horizontal adduction/abduction torque showed the most differences. Again, it is important to note that both shoulder and elbow follow-up injury group only had four pitchers so some variations could be caused by the small sample size.

There were slight differences between the injury history groups and shoulder joint loading. The shoulder and elbow follow-up injury group had only one pitcher, which limited the ability to analyze how this group differed from others. The primary differences between the follow-up injury groups and shoulder joint loading were found in the distal force, superior force, and horizontal adduction torque and in the opposite-direction inferior force and horizontal abduction torque. The ability to analyze how the shoulder and elbow injury history group differed from others was limited because there were only two pitchers. Understanding the connection between shoulder joint loading and injury mechanisms is helpful in prevention, aligning with previous reports (Seroyer et al., 2010).

Additional factors that may contribute to the relationship of shoulder joint loading and injuries which include fatigue, throwing arm kinematics, and elbow joint loading (Bullock et al., 2021; Escamilla et al., 2007; Fleisig et al., 2011; Loftice et al., 2004; Manzi et al., 2022; Matsuo et al., 2006; Pei-Hsi Chou et al., 2015; Solomito et al., 2015). A previous study showed that pelvis and trunk forward tilt as well as shoulder horizontal abduction were trade off variables because they increased ball velocity but also increased the torque (Semkewyc, 2022). This aligned with our findings that showed that the shoulder adduction angle had a statistically significant difference with the injury groups, indicating that it is a factor in both performance and injury mechanisms. Some pitchers reduce their joint loading by having a more efficient pitching motion in which their mechanics allow for a high pitch velocity and decreased loading, which would be optimal for the pitcher's longevity. More recent studies are using machine learning and statistical modeling to help predict injuries based on pitching biomechanics (Sakata et al., 2021; Stuelcken et al., 2016; Sutter et al., 2018). New technology will help aid in understanding the relationship of injury and pitching biomechanics.

There is also a large debate on what are the best pitches to throw for many reasons including performance, longevity, injury and when is the correct or best time to introduce a variety of pitches. Baseball pitches can be grouped into three main categories which include fastballs, breaking balls, and changeups. Within each of these three main categories there are a variety of different types of pitches. A comprehensive study, showed that in collegiate baseball pitchers that when comparing fastball pitches and curveball pitches there was statistically significant kinematic differences but very few kinetic differences, where the changeup pitches had much lower joint kinetics and angular velocities, and the slider it was inconclusive because of the small sample size (Fleisig et al., 2006). Where our study only focused on overhand throwing fastballs, there seems to be variation between pitches but between fastballs and breaking balls more investigations are needed. Even considerations of arm slot could affect both joint loading and injury mechanisms. There are three main arm slots that include throwing overhand, a 3/4 arm slot, or side arm, that could be additional factors. Many other studies have looked at the impacts of arm slot and pitch type and how they impact the game (Agresta et al., 2019; Escamilla et al., 2001; Escamilla et al., 2018; Norkus et al., 2001). Further, studies have investigated the effects of throwing breaking balls at the youth age and how they may be potentially more harmful but there are not clear results (Dun et al., 2008; Kerut et al., 2008; Yang et al., 2014). Overall, fastball pitches and change-up pitches are the most utilized and respected and there are varying views on breaking balls because with every pitcher having slightly different biomechanics, the loading and injury mechanisms vary.

Several studies have shown that higher ball speed can lead to increased risk of injury (Bushnell et al., 2010; Coughlin et al., 2019). This leads to the question of are professionals more likely to get injured because they are throwing much higher than youth athletes. A previous study compared the kinematic variables of teenage pitchers to 40 year old pitchers and found some very interesting results including at foot contact the older group had a shorter stride, a more closed pelvis position, and a more closed upper trunk position (Dun et al., 2007). Further, they found the older group had less shoulder external rotation during the arm cocking phase, less lead knee flexion angle, and less forward trunk tilt at ball release (Dun et al., 2007). These variations could very likely be impacting both injury risk and performance and should be further investigated at all levels. Most of the baseball pitching research has been done on youth and the professional level because of the abundance and the consistency, but only a few studies have investigated the important in between stage of collegiate baseball pitching. This is most likely because of the inherent challenges with college pitchers.

6.5. Objective 5 – Throwing Biomechanics Index for Baseball Pitching

The fifth, and final, null hypothesis was rejected because there were strong relationships between the shoulder exam variables, baseball pitching biomechanics variables, and throwing arm injury variables in comparison to the throwing biomechanics index. The results show that the no injury and high performing group had the highest throwing biomechanics index compared to the other groups but there was no statistically significant difference. There were 15 statistically significant variables that make up the throwing biomechanics index that include: stride length at foot contact, foot angle, knee angle at foot contact, maximum hip angular velocity, trunk forward angle, maximum spine lateral bend angular velocity, maximum external rotation angle, elbow angle at foot contact, maximum elbow angular velocity, peak anterior/posterior shoulder force, peak superior/inferior shoulder force, peak proximal/distal shoulder force, peak internal/external shoulder torque, resultant elbow force, and valgus/varus elbow torque. Further analysis investigated the individual scores for all fifteen variables that were used to create the index to compare across the three injury groups and the no injury and high performing group's score for each variable and there was no statistically significant difference. The no injury and high performing group has the largest mean for six of the fifteen variables.

Further diving into the relationship of the throwing biomechanics index with other variables such as the demographic variables, performance variable, and shoulder exam variables showed statistically significant relationships. For the relationship between the throwing biomechanics index and the pitcher demographic variables there was a statistically significant relationship between height, mass, age, and forearm length. For the relationship between the throwing biomechanics index and the pitcher shoulder exam variables there was a statistically significant relationships between dominant arm internal SRF, dominant arm external ROA, non-dominant arm external ROA, and dominant arm external SRF. For all the other variables there were not any statistically significant relationships with the throwing biomechanics index. Kinetic variables are dependent on height and weight so seeing those connections are obvious with the throwing biomechanics index; however, the dominant arm internal SRF, dominant arm external ROA, non-dominant arm external ROA, and dominant arm external SRF must be related to the throwing biomechanics kinematics components, which means this single index is a well reflection of collegiate throwing biomechanics.

The kinematic and kinetics variables had statistically significant relationships when using the logistic regression with the injury groups in collegiate baseball pitchers. However, when combining these variables to create a throwing biomechanics index there were trends but there were no statistically significant differences between the for the injury history, follow-up injury, follow-up injury and injury history, and the no injury and high performing groups. This methodology helps create an index that is useful in being able to evaluate the athletes.

This novel methodology leaves room for further research. The value in the index is that it gives a quantitative way to summarize all the throwing biomechanics variables. Tons of papers have investigated specific or certain types of variables or risk factors but very few have investigated a way to quantify a summary variable (DeFroda et al., 2016; Fleisig et al., 2011; Keller et al., 2017; Lyman et al., 2002; Petty et al., 2004; Shanley et al., 2011; Tyler et al., 2014). The index is useful in monitoring rehabilitation protocols as well as monitoring the pitcher’s injury risk. The higher the index the closer the pitcher is to both no injury and high performing group as we quantify by the ball speed. The results we see show that those pitchers in the follow-up injury group and the injury history and follow-up injury group have very similar index scores, while the injury history group had the lowest index score. It is interesting to consider that those who had injury histories may be using different mechanics after their rehabilitation period, and this could be impacting the overall index score. This could follow the idea that those pitchers who are more injured may have a lower index and those who are in the no injury and high performing group may have a higher index and more investigations will help give a clear picture of what is going on. It is important to note that there were eight subjects in the injury history and follow-up injury group so some variation may come from the small sample size. There are many factors that could be influencing the results of comparing injury variables with the throwing biomechanics index.

Variables seen throughout the kinetic chain spur on more investigations of how even the wind up may influence a pitchers potential injury and performance. Many studies have investigated the impact of kinetic chain impacting both injury and performance (Iwahazama et al., 2016; Mayes et al., 2022; Solomito et al., 2018; Song et al., 2020). A previous study showed that stride length impacts the entire pitching cycle, which aligns with our findings of both stride length at foot contact and foot angle being significant factors in the throwing biomechanics index (Ramsey & Crotin, 2022). This is all emphasizing the importance of evaluating all biomechanical variables as they can lead to impacting the risk of injury and performance in baseball pitchers.

Our throwing biomechanics index was related to both pitching demographic variables and shoulder exam variables. The statistically significant relationship with the height, mass, age, and forearm length could point to the connection of development and different mechanics as the pitchers develop from youth all the way to the professional level. The throwing biomechanics index also had several statistically significant relationships with the pitcher shoulder exam variables and this could lead to using the shoulder exam to be another way to monitor the health of the pitcher. These relationships show the value in the throwing biomechanics index as they can be used to gain further understanding of pitching injury mechanisms and performance.

There are several limitations of the throwing biomechanics index because it is just being introduced. Most of the limitations will be revised and improved upon with further and future work. Understanding optimal mechanics could help improve the index by specifically identifying thresholds of the no injury and high performing group to determine more accurate results. This index is intended to evaluate both injury mechanisms and performance so real game data would be useful to compare the throwing biomechanics index to quantifiable performance parameters. In two recent papers, Nicholson et al used machine learning for baseball pitchers thirteen years or older and developed an algorithm that predicts their ball velocity and their throwing arm kinetics (Nicholson et al., 2022a, 2022b). The use of machine learning could be very advantageous in determining the optimal throwing biomechanics index. The value in the throwing biomechanics index is that it could be further be investigated or expanded to all throwing athletes for example American football quarterbacks, track and field javelin throwers, and many others. Connecting the throwing biomechanics index to demographics variables, shoulder exam variables, and other clinical tests increases the knowledge in this field. There is great value in quantifying a throwing biomechanics index for both understanding the injury mechanisms and for improved performance.

6.6. Limitations

There were several limitations in this study. All tests were performed in the laboratory setting, which could affect the pitcher’s ability for maximal effort. Recording in a laboratory setting could reduce their overall intensity of the pitches because it is not a competition or even their normal settings. The pitchers had full warm up time and were encouraged and reminded to think of this as a practice setting; however, there was most likely still an impact from the settings. Another challenge to our study was trying to follow collegiate baseball pitchers for several years because some transferred, graduated, or stopped playing for other reasons. This is the inherent challenge of this age range and why there is minimal work done on collegiate baseball pitchers. Self-reported questionnaires could lead to some differences and missing results. There are varying views on self-reported questionnaires, but in our study when reporting injury or surgeries there had to be evidence of loss of playing time and they had to seek medical attention. This is thought to combat this issue to quantify injury and surgery. This is all pointing to value of continuing future work and investigating the shoulder exam variables, pitching biomechanics variables, and injury variables and their relationship to one another.

6.7. Future Work

Overall, there is a lot of potential interesting and groundbreaking work that could be investigated to push the field of baseball pitching and sports medicine forward that would ultimately improve performance and reduce injury. There were three main encouraged future works that would improve and add on to this study. The first is expanding investigations to all levels from youth to professional to see how their injury mechanisms, shoulder exam, and pitching mechanics all interact. The second is incorporating in game biomechanics and performance data to help improve the accuracy and large scheme analysis. The third and most used in all science would be increasing the sample size to help increase understanding.

Diving further into future work for all five objectives to bring clarity on ideas for growth and improvement. For objective 1, the demographic variables were investigated with shoulder exam variables, biomechanics variables, and injury variables, a large data base of pitchers of all ages would be helpful to further understand the impact of demographic variables on the game. For objective 2, the shoulder exam variables were investigated with the biomechanics variables, a study that performs shoulder exams after every pitching instance (game or practice) for one season would be interesting to be able to determine how the shoulder exam variables alter throughout the season. For objective 3, the injury variables were investigated with the shoulder exam variables, a deeper look and tracking of shoulder and elbow rehabilitation after injury would clarify injury mechanisms and identifying predicting signs before injuries occur. For objective 4, the biomechanics variables were investigated with the injury variables, a long-term study that tracks injury and biomechanics would be interesting to see a clear picture of the connection. For objective 5, the throwing biomechanics index for baseball pitching was developed and investigated, a collaboration with computer science or the use of machine learning to determine the best and optimal throwing biomechanics index that is both validated and predictive would improve the sport. These ideas for future work leave room for more ideation, advancements, and new knowledge that will push forward the sport of baseball and the field of biomechanics.

CHAPTER 7: SUMMARY

The summary chapter covers the takeaways, publications and conference proceedings, and limitations of this study. This chapter serves as an overview of what we have accomplished thus far and discusses the limitations or challenges of this study. The publications and conference proceedings serve as further evidence of this study's progress. This summary chapter concludes the thesis proposal.

7.1. Takeaways

Overall, there are many relationships between the three pillars of this study; the shoulder exam, the biomechanics, and the injury questionnaire are all components to telling the story about baseball pitching (Figure 25). The massive focus of reducing injuries and improving performance expands way beyond just baseball pitching and into all of sports medicine. The framework we developed in this study could be used and is transferable to other sports and other aspects of life.

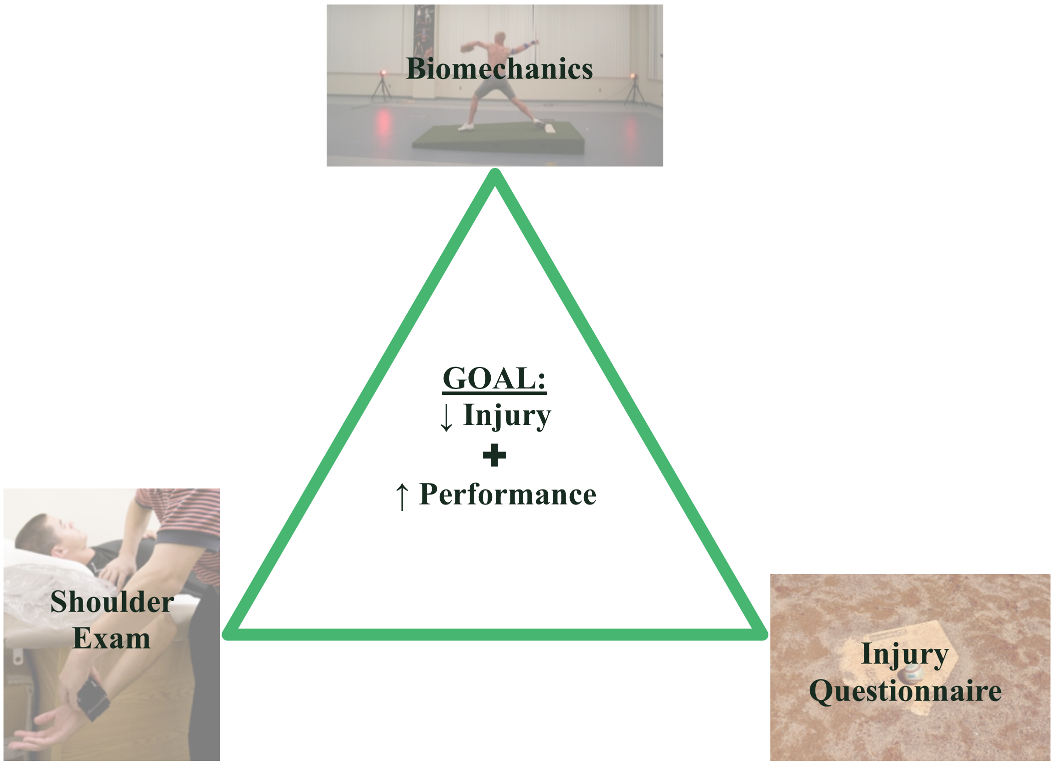

Figure 23: The takeaways come back to diving into this triangle figure that focuses on the three pillars of this study.

The first objective investigated the demographics vs. shoulder exam, biomechanics, and injury and showed many statistically significant relationships. The takeaways from objective 1include:

- The demographic variables relationship with shoulder exam variables had 13 statistically significant positive correlations and 32 statistically significant negative correlations.
- The strongest relationships between the demographic variables and shoulder exam variables were between the dominant arm internal EPA and division level and the dominant arm internal SRF and forearm length.

- The demographic variables relationship with kinematic variables had 12 statistically significant positive correlations and 21 statistically significant negative correlations.
- The strongest relationships between demographic variables and kinematic variables were between the ball speed and forearm length and the maximum external rotation angle and age.
- The demographic variables relationship with kinetic variables had 25 statistically significant positive correlations and 7 statistically significant negative correlations.
- The strongest relationships between the demographic variables and kinetic variables were the elbow SI force and mass and the shoulder SI force and mass.
- The strongest relationships between demographic variables and the injury variables were in division and follow-up years.

The second objective investigated the shoulder exam vs. biomechanics and showed many statistically significant relationships. The takeaways from objective 2 include:

- The dominant shoulder exam variables relationship with kinematic variables had 21 statistically significant positive correlations and 7 statistically significant negative correlations.
- The strongest relationships between dominant shoulder exam variables and kinematic variables were between maximum external rotation angle and external EPA and shoulder abduction angle and external EPA.

- The strongest relationships between the bilateral shoulder exam variables and kinematic variables were between maximum shoulder internal rotation angular velocity and bilateral difference internal EPA and maximum shoulder horizontal adduction angle and bilateral difference total ROM.
- The internal EPA had significant differences with the lead foot angle and the knee angle at ball release, respectively.
- The external EPA had significant differences with elbow angle at ball release, shoulder abduction angle, maximum external rotation angle, and maximum shoulder linear velocity, respectively.
- The internal ROA had significant differences with the ball speed and knee angle at ball release, respectively.
- The external ROA had significant differences with the stride length, elbow angle at ball release, shoulder abduction angle, and maximum external rotation angle, respectively.
- The internal SRF had significant differences with the maximum shoulder horizontal adduction angular velocity and maximum hip linear velocity, respectively.
- The external SRF had significant differences with the knee angle at foot contact and forward trunk angle, respectively.
- The dominant shoulder exam variables relationship with kinetic variables had 13 statistically significant positive correlations and 14 statistically significant negative correlations.

- The strongest relationships between dominant shoulder exam variables and kinetic variables were between elbow AP force and external SRF and shoulder IE torque and external ROA.
- The strongest relationships between the bilateral shoulder exam variables and kinetic variables were between elbow AP force and bilateral difference total ROM.
- The internal EPA had significant differences with superior/inferior shoulder force and resultant shoulder force, respectively.
- The external ROA had significant differences with superior/inferior shoulder force, abduction/adduction shoulder torque, internal/external rotation shoulder torque, resultant shoulder torque, medial/lateral elbow force, valgus/varus elbow torque, and resultant elbow torque, respectively.
- The internal SRF had significant differences with proximal/distal shoulder force, abduction/adduction shoulder torque, internal/external rotation shoulder torque, resultant shoulder torque, extension/flexion elbow torque, and resultant elbow torque, respectively.
- The external SRF had significant differences with internal/external rotation shoulder torque, anterior/posterior elbow force, extension/flexion elbow torque, and resultant elbow torque, respectively.

The third objective investigated the injury vs. shoulder exam and showed many statistically significant relationships. The takeaways from objective 3 include:

- There was a statistically significant relationship between the dominant throwing arm internal SRF and the injury variables.
- The dominant and non-dominant arms for internal EPA had significant differences in the follow-up injury, injury history, and no injury group, where external EPA had significant differences in the follow-up injury, injury history, and no injury group, respectively.
- The dominant and non-dominant arms for internal ROA had significant differences in the follow-up injury, injury history, no injury, and follow-up injury and injury history group, where external ROA had significant differences in the follow-up injury, injury history, no injury, and follow-up injury and injury history group, respectively.
- The dominant and non-dominant arms for internal SRF had significant differences in the no injury group and follow-up injury and injury history group, where external SRF had no statistically significant differences, respectively.

The fourth objective investigated biomechanics vs. injury and showed many statistically significant relationships. The takeaways from objective 4 include:

- For the kinematic variables, there was a statistically significant relationship between the shoulder horizontal adduction angle and the injury variables.
- For the kinetic variables, there were no statistically significant differences with the injury variables.

The fifth objective investigated the throwing biomechanics index in baseball pitchers and showed many statistically significant relationships. The takeaways from objective 5 include:

- The results show the no injury and high performing group had the highest throwing biomechanics index compared to the other groups but there was no statistically significant difference.
- For the relationship between the throwing biomechanics index and the pitcher demographic variables there was a statistically significant relationship between height, mass, age, and forearm length.
- For the relationship between the throwing biomechanics index and the pitcher shoulder exam variables there was a statistically significant relationship between dominant arm internal SRF, dominant arm external ROA, non-dominant arm external ROA, and dominant arm external SRF.
- The throwing biomechanics index is a representative value because of its relationship to both demographic and shoulder exam variables.

7.2. Publications and Conference Proceedings

Journal Publications:

- Stokes, H., Eaton, K., Zheng, N. (2021) "Shoulder External Rotational Properties During Physical Exam are Related to Injury That Requires Surgery and Shoulder Joint Loading During Baseball Pitching," *American Journal of Sports Medicine*.

- Stokes, H., Escamilla, R., Bellapianta, J., Wang, H., Beach, T., Frost, D., Zheng, N. (2023) "Open Foot Stance Reduces Lead Joint Loading During Golf Swing," *Journal of Applied Biomechanics.*

Journal Publications in Process:

- Stokes, H., Eaton, K., Zheng, N. (2023) "The Shoulder External Over Internal Rotation Ratio (SEIR) Is Related to Biomechanics in Collegiate Baseball Pitching," *Submitted to Journal of Applied Biomechanics.*
- Stokes, H., Eaton, K., Zheng, N. (2023) "The Shoulder External Over Internal Rotation Ratio (SEIR) Is Related to Injury in Collegiate Baseball Pitchers," *Submitted to Sports Biomechanics.*
- Stokes, H., Chen, F., Zheng, N. (2023) "Patient Reported Outcome Measures and Biomechanical Variables that May Be Related to Knee Functions Following Total Knee Arthroplasty," *Submitted to PLOS One.*
- Chen, F., Stokes, H., Zheng, N., (2023) "Patient Reported Outcome Measures and Biomechanical Variables that May Related to Knee Functions Following Total Knee Arthroplasty," *Submitted to Heliyon.*

Conference Papers:

- Stokes, H., Eaton, K., Zheng, N. (2023) "Investigations of the Throwing Biomechanics Index in Collegiate Baseball Pitchers," *11th International Conference on Sports Sciences Research and Technology Support.*

Conference Proceedings, Poster Presentations, and Abstracts:

- Stokes, H., Chen, F., Singer, R., Bates, M., Zheng, N. (2024) “Enhancing Understanding and Correlation of Patient-Reported Outcomes and Biomechanical Measures in Total Knee Arthroplasty,” submitted to the Orthopaedic Research Society.
- Chen, F., Stokes, H., Singer, R., Bates, M., Zheng, N. (2024) “Knee Biomechanics Index of Patients with Total Knee Arthroplasty in Different Daily Activities,” submitted to the Orthopaedic Research Society.
- Stokes, H., Eaton, K., and Zheng, N. (2023) “Quantifiable Shoulder Exam Measurements Are Related to Throwing Arm Injuries in Collegiate Baseball Pitchers,” presented at the Orthopaedic Research Society.
- Stokes, H., Chen, F., Singer, R., Bates, M., Zheng, N. (2023) “Investigating Quadriceps Muscle Activity and Pain Level Climbing Stairs for Total Knee Arthroplasty Patients,” presented at the Orthopaedic Research Society.
- Chen, F., Stokes, H., Singer, R., Bates, M., Zheng, N. (2023) “Limb Symmetry of the Knee Joint Kinematics During Daily Activities for Total Knee Arthroplasty Patients,” presented at the Orthopaedic Research Society.
- Stokes, H., Eaton, K., and Zheng, N. (2022) “The Shoulder External Over Internal Rotation Ratio Is Related to Injury in Collegiate Baseball Pitching,” presented at the World Congress of Biomechanics.
- Stokes, H., Eaton, K., and Zheng, N. (2022) “Shoulder External Over Internal Rotation Ratio for Throwing Athletes,” presented at the World Congress of Biomechanics.

- Stokes, H., Escamilla, R., Bellapianta, J., Wang, H., Beach, T., Frost, D., and Zheng, N. (2022) "Foot Stance Is Related to Target Knee Joint Biomechanics During Golf Swing," presented at the World Congress of Biomechanics.
- Chen, F., Stokes, H., Singer, R., Bates, M., and Zheng, N. (2022) "Electromyography Analysis of Knee Joint Muscles for TKA Patients During Sit-to-Stand Test," presented at the World Congress of Biomechanics.
- Stokes, H., Eaton, K., and Zheng, N. (2022) "Shoulder Abduction Angle and Lateral Trunk Tilt Are Related to Throwing-Arm Joint Loading During Collegiate Baseball Pitching," presented at the World Congress of Biomechanics.
- Stokes, H., Eaton, K., and Zheng, N. (2022) "Peak Throwing-Arm Joint Loading Is Not Related to Injuries in Collegiate Baseball Pitchers," presented at the Orthopaedic Research Society.
- Stokes, H., Eaton, K., and Zheng, N. (2022) "Pitching Mechanics Are Related to Throwing-Arm Injuries in Collegiate Baseball Pitchers," presented at the Orthopaedic Research Society.
- Stokes, H., Eaton, K., and Zheng, N. (2021) "Injury and Surgery Are Associated with Shoulder External Rotation During Exam and Baseball Pitching," presented at the International Society of Biomechanics.
- Stokes, H., Duemmler, M., Eaton, K., and Zheng, N. (2021) "Correlation of Glenohumeral Internal Rotation Deficit, Total Range of Motion, and Retroversion to Shoulder Kinetics in Collegiate Baseball Pitchers," presented at the International Society of Biomechanics.

- Duemmler, M., Stokes, H., Eaton, K., and Zheng, N. (2021) "Shoulder Internal Rotation Deficit and Total Rotational Motion Deficit of the Throwing Arm Are Not Related to Injuries and Surgeries in Collegiate Baseball Pitchers," presented at the American Society of Biomechanics.
- Stokes, H., Eaton, K., and Zheng, N. (2020) "Shoulder External Rotation ROM During Physical Exam Is Related to the Joint Loading During Baseball Pitching," presented at the American Society of Biomechanics.
- Stokes, H., Eaton, K., and Zheng, N. (2020) "External Shoulder Flexibility During Physical Exam Is Related to Shoulder Joint Loading During Baseball Pitching," presented at the American Society of Biomechanics.
- Stokes, H., Eaton, K., and Zheng, N. (2020) "Shoulder Rotational Properties During Physical Exam Are Related to Performance and Injury During Baseball Pitching," presented at the American Society of Biomechanics.
- Callahan, C., Stokes, H., Singer, R., Bates, M., Zheng, N. (2020) "Patient Perceived Pain and Function Measures Are Related to Biomechanical Measures in TKA Patients," presented at the American Society of Biomechanics.

7.3. Conclusions

In conclusion, the investigation of the three pillars (shoulder exam, biomechanics, and injury questionnaires) in this study produced many new insights for collegiate baseball pitchers. Traced throughout the entire study and future work the focus remains on how we improve performance and reduce injuries, and this expands beyond just the sport of baseball. Our findings show that optimizing pitching mechanics and shoulder flexibility reduce injury and improve performance. Pitching mechanics is comprised of kinematics and kinetics and improvement is found when pitching with proper mechanics. Shoulder flexibility is monitored and improved by proper warm up and cool down stretching protocols. This new understanding serves two main purposes: helps create new rehabilitation protocols and serves as a screening for athletes to identify risk of injuries and monitor when they can return to sport. For both, the goal is to ensure strong and healthy joints. Allowing athletes to get back in the game and further anyone with shoulder or elbow injuries back to their everyday life. Ultimately, pushing forward humanity's potential for good.

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APPENDIX A: Institutional Review Board Data Bank Approval

Hannah Stokes <hstokes3@uncc.edu>

IRB Notice - 19-0805

IRB <uncc-irb@uncc.edu> Thu, Jul 2, 2020 at 7:30 AM
To: hstokes3@uncc.edu, nzheng@uncc.edu
Cc: uncc-irbis@uncc.edu

To: Hannah Stokes
Mechanical Engineering and Engineering Science

From: Office of Research Protections and Integrity

Date: 7/02/2020
RE: Notice of Approval of Exemption with No End Date
Exemption Category: 4.Secondary data/specimens
Study #: 19-0805

Study Title: Shoulder Rotational Properties Are Related Injury and Shoulder Kinetics During Baseball Pitching

This submission has been reviewed by the Office of Research Protections and Integrity (ORPI) and was determined to meet the Exempt category cited above under 45 CFR 46.104(d). This determination has no expiration or end date and is not subject to an annual continuing review. **However, you are required to obtain IRB approval for all changes to any aspect of this study before they can be implemented.**

Study Notes:

- Per University mandate in response to the ongoing Coronavirus Disease 2019 (COVID-19) outbreak, all Human Subjects Research activities involving on-campus implementation **and/or** direct person-to-person contact should not proceed until University restrictions are lifted.
- Restoring and restarting direct person-to-person Human Subjects Research activities, must have University-level approval. Refer to the Research Restart and Restoration Task Force Report and the Office of Research Protections and Integrity guidelines.
- Further, activities occurring off-campus must adhere to local, state, and federal restrictions (including stay-at-home orders) as well as public health requirements for the size of groups/gatherings, social distancing, hygiene, and sanitization, etc.
- Protocol Modifications are needed to adjust data collection procedures to remote data collection (e.g., phone, online or virtual).

The Investigator Responsibilities listed below apply to this study only. Carefully review the Investigator Responsibilities.

Study Description:

Injuries are common during baseball pitching because of the demand on the shoulder. The purpose was to investigate the relationship between injury history, shoulder rotational properties and shoulder joint loading in baseball pitchers. Knowledge of shoulder rotational properties and shoulder joint loading may provide new insights for treatments to reduce the likelihood of injury incidences.

Your approved consent forms (if applicable) and other documents are available online at http://uncc.myresearchonline.org/irb/index.cfm?event=home.dashboard.irbStudyManagement&irb_id=19-0805.

Investigator's Responsibilities:

The above-cited determination has no expiration or end date and is not subject to annual continuing review.

However, the Principal Investigator needs to comply with the following responsibilities:

1. Modifications **must** be submitted for review and approval before implementing the modification. This includes changes to study procedures, study materials, personnel, etc.
2. Data security procedures must follow procedures as approved in the protocol and in accordance with ITS Guidelines for Data Handling.
3. Promptly notify the IRB (uncc-irb@uncc.edu) of any adverse events or unanticipated risks to participants or others.
4. Complete the Closure eform via IRBIS once the study is complete.
5. Be aware that this study is now included in the Office of Research Protections and Integrity (ORPI) **Post-Approval Monitoring program** and may be selected for post-review monitoring at some point in the future.
6. Reply to ORPI post-review monitoring and administrative check-ins that will be conducted periodically to update ORPI as to the status of the study.
7. Three years (3) following this Exemption determination, ORPI will request a study status update (active/not active).

Please be aware that approval may still be required from other relevant authorities or "gatekeepers" (e.g., school principals, facility directors, custodians of records).

APPENDIX B: Participation Recruitment Letter

UNC CHARLOTTE

The University of North Carolina at Charlotte
9201 University City Boulevard
Charlotte, NC 28223-001
THE WILLIAM STATES LEE Department of Mechanical Engineering COLLEGE OF ENGINEERING and Engineering Science 704/687-8253
FAX: 704/687-8345

Re: Participation in MLB Sponsored Clinical Research at UNC Charlotte

We are conducting a Major League Baseball (MLB) sponsored research study at UNC Charlotte. Our study consists of testing the shoulder laxity or flexibility of pitchers, pitching mechanics using high-speed motion analysis system, as well as collecting injury data from each player. The test protocol was reviewed by our Co-Principal Investigator, Dr. Koco Eaton, team physician of Tampa Bay Rays, and approved by university's institutional review board (IRB) and MLB medical committee.

The objective of this project is to relate the shoulder laxity to potential injuries of the throwing arm. Here are answers to frequently asked questions:

1. *Where?* All tests will be conducted at the UNC Charlotte.
2. *How long will it take to complete the paperwork?* – Less than 5 minutes. It is the same injury questionnaires they fill out last year. For those who have participated in the study in the past, they don't need to fill out the consent form which is good for the whole study (3 years). For those who did not participate last year they have to sign the consent form.
3. *How long will it take one guy to complete the whole body scan?* The whole body scan takes only 17 seconds, it saves time for us to take measures from each player, such as height, arm length etc.
4. *How long will it take to complete the laxity test per player?* It takes approximately 7 minutes for the laxity test per guy.
5. *How long will it take to do the motion analysis of pitching mechanics?* It will take about 30 minutes. If your guys have warmed up and completely loose out in the field, we just attach 17 reflective beads on their major joints, ask them to through ***10 fast balls*** from our portable mound in our lab. We will get three best fastballs (strike, highest speed) for data analysis.
6. *How many players can you test in one day?* In the past, we have tested 10 college teams. We tested 6 to 8 players each evening. We tested a whole team (16 players) one day on weekends. We scheduled a player every 45 minutes and most time we finished tests earlier. I would like to test all your pitchers in two to three days.
7. *When is the best time for us to come for the study?* We would like to test them later afternoon and evenings on weekday, or any time on weekends.
8. *Will you test just one or two players?* Yes.

9. *Will we get paid?* **No.**
10. *Will we get billed?* **No.** The funding from Major League Baseball allows us to test college players for free. Those tests cost about $1000 per subject. We charged $500-$1000 per subject in the past. Please take this advantage for free biomechanical evaluations.

You can contact me with questions or concerns at 704-687-7301 or nzheng@uncc.edu. Thank you very much for your time and I hope to hear from you soon.

Sincerely,

Nigel Zheng, Ph.D.

Principal Investigator
MLB Clinical Research Project
Director, Biomechanics and Motion Analysis Laboratory
University of North Carolina at Charlotte
704-687-7301
nzheng@uncc.edu

APPENDIX C: Institutional Review Board Data Bank Retrieval Consent Forms

UNC CHARLOTTE
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and Engineering Science
704/687-8253
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Informed Consent for Biomechanics Motion Analysis Laboratory Data Bank

If you are a parent, as you read the information in this Consent Form, you should put yourself in your child's place to decide whether or not to allow your child to take part in this study. Therefore, for the rest of the form, the word "you" refers to your child.

If you are a child or adolescent reading this form, the word "you" refers to you.

We (Nigel Zheng, Ph.D. and assistants) are asking permission from you,

____
Printed name of study participant ("study subject")

to store some of your medical information which you provide to us. The Principal Investigator (the person in charge of this research) or a representative of the Principal Investigator will also describe this data bank to you and answer all of your questions. Your participation is entirely voluntary. Before you decide whether or not to take part, read the information below and ask questions about anything you do not understand. If you choose not to participate in this study you will not be penalized or lose any benefits that you would otherwise be entitled to.

The choice to let Nigel Zheng, Ph.D. keep your data for doing research is entirely up to you. If you decide that your data can be kept for research but you later change your mind, tell Nigel Zheng, Ph.D. at (704) 687-7301 who will remove and destroy any of your data that he still has. Otherwise, the data may be kept until Nigel Zheng, Ph.D. decides to destroy them. You have the right to see and copy the information that is collected from you and stored in the data bank. There will be no cost to you for any data collected and stored.

If you agree, the following data will be collected and stored in the data bank:

- Records of physical exams and physical measurements of your body segments
- Results from the Motion Analysis
- Results from Biomechanical evaluations
- Diaries and questionnaires
- Videotape records from the Motion Analysis
- Ultrasound and/or MRI results, if requested by us.

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Your participation will include completing questionnaires about your health and medical history. We will measure you height, weight, body fat, and take measurements of your body. If you have experienced any type of joint injury, we will discuss this with you and ask you to describe the injury and the treatment you received or are still receiving. Then we'll ask you to warm up as you would normally do before performing exercise or a sports activity. We'll attach reflective sphere beads to your body and have you to walk, run, or perform the normal motions of your sport activity. While you do this we will be video and audio recording your movements. We will also be collection data from each of the reflective sphere beads we placed on your body. All of this information will be stored in our data bank so that we can use it later. For example, we may want to look at all the motion data we collected from individuals with knee injuries.

Your data will be kept in a secure location in a data bank called the University of North Carolina at Charlotte Biomechanics/Motion Analysis Laboratory Data Bank so that it may be used in future research to learn more about your medical condition and other medical problems. Once collected, you may be called from time to time to update information on your health that is necessary to keep the data bank current.

Although every effort will be made to keep your information confidential, there is a small risk that an unauthorized person may obtain your information. Therefore, there is a very slight risk that a test result could be linked to your identity and inadvertently disclosed to a third party. In addition, you might have to decide whether or not to discuss the findings with members of your family. If a third party (like your employer or insurer) learned the results, there is a risk of discrimination that could affect your employability or insurability, of stigma, and of the unpredicted disclosure of this information to others.

Nigel Zheng, Ph.D. and associates will be allowed to collect, use and/or give out your data. They may give your data to other researchers whose research is approved by an Institutional Review Board (IRB) (An IRB is a group of people who are responsible for looking after the rights and welfare of people taking part in research). They may also give your data to a study sponsor, the Food and Drug Administration, the Department of Health and Human Services, the Office of Human Research Protections, or other Government agencies. There is a risk that information received by these authorized persons or agencies could then be passed on to others beyond your authorization and not covered by the law.

In general, presenting research results helps the career of a scientist. Therefore, the Principal Investigator may benefit if the results of this study are presented at scientific meetings or in scientific journals. Although your data will never be sold, it is possible that new treatments, medicines, therapies or products could be created from studies that use your data. If that happens, the Principal Investigator and the University of North Carolina at Charlotte could receive significant financial benefits. You will not be offered any payment or any other financial benefit.

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Signatures

As a representative of this study, I have explained to the participant the purpose, the procedures, the possible benefits, and the risks of this research study; the alternatives to being in the study; and how the participant's protected health information will be collected used and shared:

____ ____________________
Signature of Person Obtaining Consent & Authorization Date

Consenting Adults. You have been informed about this study's purpose, procedures, possible benefits, and risks; the alternatives to being in the study; and how your protected health information will be collected, used and shared. You will get a copy of this Form. You have been given the opportunity to ask questions before signing this form, and you have been told that you can ask other questions at any time.

Adult Consenting for Self. By signing this form, you voluntarily agree to participate in this study and hereby authorize the collection, use and sharing of your protected health information as described in sections 17-26 above. By signing this form, you are not waiving any of your legal rights.

____ ____________________
Signature of Adult Consenting & Authorizing for Self Date

Parent/Adult Legally Representing the Subject. By signing this form, you voluntarily give your permission for the person named below to participate in this study and hereby authorize the collection, use and sharing of protected health information for the person named below as described in sections 17-26 above. You are not waiving any legal rights for yourself or the person you are legally representing. After your signature, please print your name and your relationship to the subject.

____ ____________________
Consent & Authorization Signature Date
of Parent/Legal Representative

____
Print: Name of Legal Representative of and Relationship to Participant:

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Participants Who Cannot Consent But Can Read and/or Understand about the Study. Although legally you cannot "consent" to be in this study, we need to know if you want to take part. If you decide to take part in this study, and your parent or the person legally responsible for you gives permission, you both need to sign. Your signing below means that you agree to take part (assent). The signature of your parent/legal representative above means he or she gives permission (consent) for you to take part.

____ _______________
Assent Signature of Participant Date

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Consent to be Videotaped and to Different Uses of the Videotape(s)

With your permission, you will be videotaped during this research. Your name or personal information will not be recorded on the videotape, and confidentiality will be strictly maintained. When these videotapes are shown, however, others may be able to recognize you.

The Principal Investigator of this study, Nigel Zheng, Ph.D., will keep the videotape(s) in a locked cabinet. These videotapes will be shown under his direction to students, researchers, doctors, or other professionals and persons.

Please sign ***one*** of the following statements that indicates under what conditions Dr. Zheng has your permission to use the videotape.

I give my permission to be videotaped solely for this research project under the conditions described.

______________________________Signature ____________________________Date

I give my permission to be videotaped for this research project, as described in the Informed Consent Form, and for the purposes of education at the University of North Carolina at Charlotte.

______________________________Signature ____________________________Date

I give my permission to be videotaped for this research project, as described in the Informed Consent Form; for the purposes of education at the University of North Carolina at Charlotte; and for presentations at scientific meetings outside the University.

______________________________Signature ____________________________Date

APPENDIX D: Throwing Arm Injury Questionnaire

MLB Clinical Research
THROWING ARM INJURY QUESTIONNAIRE

This questionnaire will ask you about the frequency and location of throwing arm injuries over the past year.

Please feel free to ask questions: phone: 704-687-7301, nzheng@uncc.edu

GENERAL INFORMATION

DATE________________________ TEAM________________________

NAME________________________ ___Right-handed or ___Left-handed

Date of Birth ___________________ Class ___Freshman ____Sophomore ____Junior ____Senior

Height__________ Weight ____________

Were you a starter or relief pitcher over the past year? Starter: ____Relief: ____Both:_____

How many years have you pitched competitively?_______________________

Surgery __________________________ performed in (month/year)_____________

Surgery __________________________ performed in (month/year)_____________

Surgery __________________________ performed in (month/year)_____________

1. In the past year, did you suffer from any throwing arm injuries/pain that made you unable to fully participate in throwing activities during practice, unable to practice at all, or unable to compete in a game?

YES Please answer questions 1a-1d below. **NO** Please move on to #2.

1a. In the past year, how many days/weeks were you unable to participate in throwing activities during practice, unable practice at all, or unable to compete in a game because of throwing arm injuries/pain?

__________ days ____________ weeks

1b. When did the symptoms begin?

1c. Circle the general area of the throwing arm where the injury/pain occurred.

Shoulder **Elbow** **Both** **Other__________________**

1c. Circle any specific location(s) of the shoulder and/or elbow where the injury/pain occurred.

Shoulder: **anterior, posterior, superior, lateral, multiple**

Elbow: **medial, lateral, medial and lateral, internal, posterior**

1d. Did you see a physician about your throwing arm injury/pain?

YES What was your doctor's diagnosis?___________________ **NO**

2. Currently, are you experiencing any throwing arm pain during practice and/or games?

YES Please answer questions 2a-2d below. **NO** Thank you for your time.

2a. Circle the general area of the injury/pain.

Shoulder **Elbow** **Both** **Other__________________**

2b. Circle any specific location(s) of injury/pain on the shoulder and/or elbow.

Shoulder: **anterior, posterior, superior, lateral, multiple**

Elbow: **medial, lateral, medial and lateral, internal, posterior**

2c. Is the pain severe enough to negatively influence your pitching performance (velocity or control)?

YES **NO**

2d. Do you feel that you have altered your pitching mechanics because of the pain?

YES **NO**