Correlations Between Shoulder Rotational Motion, Strength Measures and Throwing Biomechanics in Collegiate Baseball Pitchers

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CORRELATIONS BETWEEN SHOULDER ROTATIONAL MOTION, STRENGTH MEASURES AND THROWING BIOMECHANICS IN COLLEGIATE BASEBALL PITCHERS

by

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ABSTRACT
CORRELATIONS BETWEEN SHOULDER ROTATIONAL MOTION, STRENGTH MEASURES AND THROWING BIOMECHANICS IN COLLEGIATE BASEBALL PITCHERS

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Pitching involves high stresses to the arm that may alter soft tissue responsible for controlling biomechanics. It has been hypothesized that imbalances in strength and flexibility of the dominant shoulder lead to decreased performance and increased injury risk, but it is not fully known what specific pitching biomechanics are altered. There is a *critical need* to determine correlations between shoulder rotational strength, range of motion and pitching kinetics. Without such knowledge, identifying potential for injury from shoulder imbalances will likely remain difficult and invasive. The *goal* of this study was to determine correlations between shoulder rotational strength and range of motion and kinetics.

Twelve collegiate pitchers participated in this IRB approved study. The clinical measures session tested shoulder rotational range of motion and strength and grip strength. The motion analysis session tested pitching biomechanics. Paired t-tests investigated differences in strength and range of motion between arms. Linear regression was performed to determine correlations between clinical measures, kinetics and pitch velocity. Regression learner neural networks were created to predict pitch velocity and elbow varus torque using clinical measures as inputs.

The dominant arm had significantly higher external rotation and total range of motion than the nondominant arm. The nondominant arm normalized external rotation peak torque was significantly greater than the dominant arm at 0˚ external rotation. Correlations were found between elbow varus torque and isometric external/internal rotation ratio, and between shoulder posterior shear force and isokinetic eccentric external rotation/internal rotation ratios. Correlations to velocity included grip strength, concentric external rotation peak torque, isometric internal rotation peak torques, and isometric external rotation peak torques. The neural network accurately predicted velocity, with the standard deviation of the error equal to 2.29 (2.97%).

These correlations associate two testing methods to identify injury risk. Increasing external/internal rotation ratios may decrease elbow varus torque and shoulder posterior shear force. Increasing external rotation, internal rotation, and grip strength may lead to velocity gains. Velocity can be predicted using clinical measures and a neural network.

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LIST OF ACRONYMS

ER	External Rotation
IR	Internal Rotation
ROM	Range of Motion
ER/IR	External Rotation/Internal Rotation
PT	Peak Torque
BW	Body Weight
3D	Three-dimensional
GIRD	Glenohumeral Internal Rotation Deficit
C3D	Coordinate 3-Dimensional
LCS	Local Coordinate System
GCS	Global Coordinate System
LL	Leg Lift
FC	Foot Contact
BR	Ball Release
MER	Maximum External Rotation
MIR	Maximum Internal Rotation
SLAP	Superior Labral from Anterior to Posterior
UCL	Ulnar Collateral Ligament
D	Dominant
ND	Nondominant
C	Collegiate
HS	High School

PRO	Professional
Y	Youth
MKH	Maximum Knee Height
HSP	Hand Separation
EE	Elbow Extension
NN	Neural Network
RLNN	Regression Learner Neural Network
SVM	Support Vector Machine
RMSE	Root Mean Square Error
MAE	Mean Absolute Error
MSE	Mean Square Error
EVT	Elbow Varus Torque
ISM	Isometric
SPSF	Shoulder Posterior Shear Force
ECC	Eccentric
SAT	Shoulder Adduction Torque
EAT	Elbow Adduction Torque
SIRT	Shoulder Internal Rotation Torque
SERT	Shoulder External Rotation Torque
IRT	Internal Rotation Torque
GS	Grip Strength

CHAPTER 1: INTRODUCTION

Baseball pitching involves repetitive, high stresses to the dominant (D) arm that may alter the soft tissue responsible for controlling the biomechanics. Over time, pitchers often develop a shift in D arm glenohumeral shoulder rotational range of motion (ROM) that either increases external rotation (ER) ROM, decreases internal rotation (IR) ROM, or both [1–4]. Similarly, the strength of the glenohumeral rotator muscles is often tested to investigate alterations to the D arm [5–12]. These interlimb strength differences are compared using shoulder external rotation to internal rotation (ER/IR) ratios of peak torque [5–12]. Lower D arm ER/IR ratios indicate weaker ER muscles, stronger IR muscles, or both when compared to the nondominant (ND) arm. These imbalances in flexibility and strength in the opposing muscles of the throwing shoulder may cause decreased performance and injury [6].

It has been hypothesized that imbalances in strength and flexibility of the D shoulder of baseball pitchers lead to a decrease in performance and increase in injury risk, but it is not fully known what specific pitching biomechanics are altered by these imbalances. There have been several studies showing the existence of these shifts in shoulder parameters [1,5–11,13,14], along with numerous pitching biomechanical studies using motion analysis techniques identifying key points of high stresses and torques [15–18]. Only one study links the strength imbalances to specific pitching kinetics [13]. Thus, there is a *critical need* to determine the correlations between shoulder rotational strength, ROM and biomechanical metrics of the pitching motion. Without such knowledge, identifying potential for performance decline and injury from shoulder imbalances will likely remain difficult and invasive.

The *goal* of this study was to determine correlations between shoulder rotational strength, ROM, and kinetics during pitching determined by motion analysis. The central hypothesis was that correlations exist between ER/IR ratios and pitching kinetics. This hypothesis has been formulated based on findings by Hurd et al. who found a positive correlation between peak shoulder ER moment and clinically measured IR strength, along with a negative correlation between peak shoulder IR moment and clinically measured ER ROM [13]. The rationale of this study is that new evidence on relationships between clinical measures and pitching biomechanics would associate different modalities of testing (i.e. strength, ROM, motion analysis, neural networks (NN)) to identify risk of injury, which would be useful to medical and coaching staff alike. It may reveal strength and flexibility training strategies to decrease abnormally high kinetics. This study achieved the goal by completing the following specific aims:

Specific Aim 1: Determine clinical measures of shoulder strength and flexibility and grip strength.

Hypothesis 1: Significant differences will be found between D and ND IR ROM, and ER ROM.

Hypothesis 2: Significant differences will be found between D and ND ER/IR ratios.

Hypothesis 3: Significant differences will be found between D and ND grip strength.

Specific Aim 2: Analyze pitching biomechanics using high-speed, three-dimensional (3D) motion analysis to determine correlations between clinical measures and biomechanics.

Hypothesis 4: Inverse correlations will be found between rotational strength ratios and key pitching kinetics.

Specific Aim 3: Develop and train a NN using strength, flexibility and biomechanics metrics.

Hypothesis 5: Trained NNs can predict key biomechanical metrics using clinical data.

We expect to determine how shoulder strength and flexibility in collegiate pitchers affect pitching biomechanics by determining the correlations between clinical measures and kinetics. This will fill the critical need of determining injury risks to pitchers associated with strength and flexibility imbalances in the shoulder. This knowledge will associate different modalities of testing baseball pitchers to identify risk of injury, along with providing training recommendations to restore balance to the shoulder and decrease high kinetics correlated with injury. Furthermore, NNs may be useful for predicting key biomechanics of pitching using clinical metrics, avoiding the need for motion analysis or maximal effort pitching.

The following section summarizes the current literature on ROM, grip strength, isokinetic and isometric strength testing, and motion analysis of baseball players. These studies establish the present status of the problem, rationale for the current study, and various aspects of the proposed protocol.

CHAPTER 2: LITERATURE REVIEW

The purpose of this chapter is to review literature relevant to the topic and to increase understanding of the purpose of this study. Key terminology, metrics of interest, and relevant previous findings will be discussed. Content includes: phases of pitching (section 2.1), common injuries associated with pitching (section 2.2), motion analysis studies that quantify biomechanics, investigate correlations of pitching metrics, and compare different populations of pitchers (section 2.3), clinical measures of pitching including strength and flexibility (section 2.4), and correlations between clinical measures and biomechanics (section 2.5).

2.1 PHASES OF PITCHING

The pitching motion is commonly divided into 6 phases: wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow through (figure 2.1). These phases are separated by key points, including foot contact (FC), maximum shoulder external rotation (MER), ball release (BR), and maximum shoulder internal rotation (MIR) [15–18]. Most peak forces and torques occur at or near these points [17]. FC marks the end of the stride, where hip rotation and lateral trunk movement begin [17,18]. During arm cocking, between FC and MER, the shoulder is externally rotating [15–18]. Just before MER, peak torques occur for shoulder IR and elbow varus torque [15,16]. During arm acceleration, between MER and BR, the arm rapidly accelerates in IR [15–18]. This action is plyometric for the anterior shoulder, as it concentrically contracts shortly after being stretched in ER. BR marks the end of the acceleration phase, and the beginning of the deceleration phase [15–18]. The posterior shoulder muscles attempt to

decelerate the IR of the arm and prevent distraction, horizontal adduction, and IR motion [16]. The deceleration phase ends with MIR, where the posterior shear force and horizontal abduction torque peak [15–18]. The follow through phase allows the pitcher to finish the arm motion and be in a prepared position to defend against a hit ball.

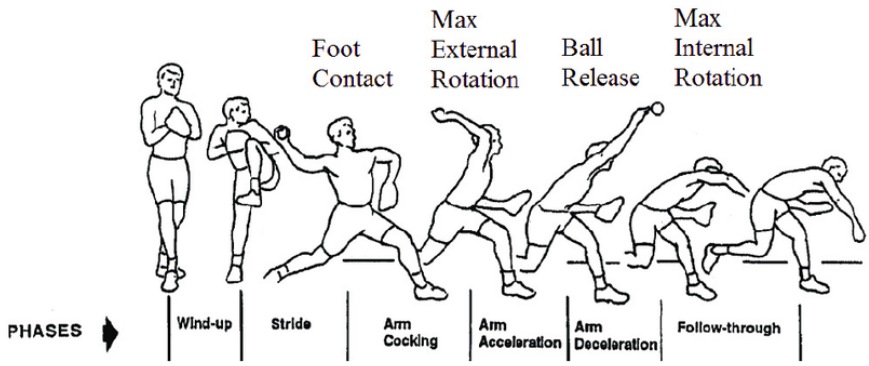

Figure 2.1: Phases and key points of the pitching motion [18].

When discussing the kinetics of pitching, it is important to clarify the difference between internal and external torques and forces. External torque is created by gravity, weight and friction, whereas internal torque is created by muscle contractions, ligamentous restraints and bony supports. For example, during the arm cocking phase, valgus torque is produced at the elbow joint (external torque) due to arm position and gravity, which is resisted by the surrounding muscles and ligaments that generate a varus torque (internal torque). While valgus and varus torque are equal and opposite, they are used interchangeably throughout pitching biomechanics literature, as are other equal and opposite torques and forces.

2.2 PITCHING INJURIES

Baseball pitching is a dynamic, repetitive, high-stress motion that often results in injury. Injuries to the throwing shoulder are the most common type of injury experienced by pitchers, and include overuse tendinitis, rotator cuff tears, glenoid labrum fraying, labral detachment, and capsular laxity problems [19]. Throwing requires the glenohumeral joint to undergo a large ROM at a high velocity while maintaining joint stability. Shoulder joint angular velocities have been reported over 7000 ˚/sec during the acceleration phase of pitching [19]. The muscles responsible for shoulder IR, including the subscapularis, anterior deltoid, pectoralis major, latissimus dorsi, and teres major, contract concentrically during the acceleration phase to internally rotate the arm at the glenohumeral joint. After BR, the external rotators, including the infraspinatus, teres minor, posterior deltoid, and supraspinatus, contract eccentrically to decelerate the arm. If the forces and torques demanded during the pitching motion surpass the limits of the muscles, injury is likely to occur [19].

The muscles of the shoulder, particularly those responsible for ER such as the infraspinatus and teres minor, are commonly injured during the deceleration phase of pitching. Microtrauma, inflammation, and decreased muscular performance allow for increased joint laxity and humeral head translation, creating a higher stability demands on the surrounding tissue. The humeral head translation causes fibrous degeneration, tissue damage, altered mechanics, and injury [19]. Pitching requires stability that must be accounted for primarily by soft tissue since the ball and socket joint of the shoulder is extremely shallow. Inflammation and pain in the posterior glenohumeral capsule (posterior capsulitis) is a sign of posterior rotator cuff tendinitis [19].

Tensile lesions to the underside of the rotator cuff are another common injury occurring during the deceleration phase. Obvious weakness of the rotator cuff is not always present in pitchers but can most often be found via isokinetic strength testing of the external rotator muscles at 90˚ shoulder abduction [19]. The arm position of 90˚ of shoulder abduction and elbow flexion is useful to test strength of pitchers due to the similarity of the arm position during pitching. Rehabilitation from tensile lesions includes strengthening the rotator cuff, with an emphasis on eccentric contractions [19]. Attention and research must be applied to identifying ways to strengthen the shoulder musculature and prevent injuries, particularly those occurring during the deceleration phase due to eccentric overload.

The glenoid labrum is another tissue commonly injured in the pitching shoulder. The labrum increases the congruency of the loose-fitting ball-and-socket glenohumeral joint. The humeral head moves from anterior to posterior in the glenohumeral joint and undergoes large compressive and shear forces [19]. The superior labrum anterior-posterior (SLAP) lesion is a common labrum lesion that results from these forces, and involves a tear on the superior portion of the labrum anterior and posterior to the biceps tendon proximal attachment [19,20]. Common side effects in pitchers with SLAP lesions include clicking, popping, shoulder pain, and decreased velocity. Glenoid labrum tears are commonly treated via arthroscopic surgery, although nonsurgical treatment, while uncommon for pitchers, may be administered depending on the type of tear [20].

The elbow joint also undergoes extremes of velocity, acceleration, forces, and torques during the pitching motion. Composed of anterior, posterior, and transverse oblique bundles, the ulnar collateral ligament (UCL) absorbs high valgus torques during

the arm cocking phase of pitching [16]. During the acceleration phase of pitching, the elbow joint is pushed near its limit, undergoing valgus forces of 64 Nm and compressive forces of 500 N as the elbow moves from 110 to 20˚ of flexion at rotational velocities of 3000 ˚/sec [21]. Valgus extension overload syndrome is the combination of large valgus torques with rapid elbow extension, which produces tensile stress along the medial compartment, shear stress in the posterior compartment and compression stress laterally [21]. Valgus torque is arguably the most important kinetic metric obtained via motion analysis to monitor due to its correlation to injury [16,22].

Tensile stress along the medial compartment affects the UCL, flexor-pronator mass, medial epicondyle apophysis, and ulnar nerve [21]. The shear stress affects the postmedial tip of the olecranon and the trochlear/olecranon fossa [21]. The lateral compression stress affects the radial head and capitellum [21]. Injury to the UCL is particularly debilitating. When torn, UCL reconstruction, also known as Tommy John surgery after the first pitcher to successfully come back from the surgery, is often required and involves a recovery period of a year or more [23]. As of 2015, 25% of all active MLB pitchers had already undergone Tommy John surgery at least once in their career [24]. Identifying ways to improve pitching biomechanics and decrease excessive torque on the elbow is important to prevent damage to the elbow joint and its surrounding tissue.

2.3 BIOMECHANICS OF PITCHING AND MOTION ANALYSIS

To accurately and effectively analyze the biomechanics of the pitching motion, a quantitative tool is necessary. Motion analysis has been the gold standard to

quantitatively describe the pitching motion for over 30 years because of the accurate biomechanical data it provides [15–17,25–33]. Elbow and shoulder kinetic measures from biomechanical studies are compared in table 2.1. These kinetics are important because they have been correlated with injury [16,22].

Table 2.1: Comparison of kinetic measures from various studies (Y=youth, HS=high school, C=college, PRO=professional, arm slot: OH=overhand, SA=sidearm, 3Q=three-quarters, Nm=Newton-meters, N=Newtons).

Study	Subjects	Elbow Varus Torque (Nm)	Shoulder IR Torque (Nm)	Shoulder Compressive Force (N)
Feltner et al. – 1986 [15]	8 – C	100 ± 20	90 ± 20	860 ± 120
Fleisig et al. – 1995 [16]	26 – PRO	64 ± 12	67 ± 11	1090 ± 110
Aguinaldo et al. – 2007 [28]	38 – Y, HS, C, PRO	N/A	Y – 33 ± 3 HS – 66 ± 6 C – 78 ± 9 PRO – 78 ± 9	N/A
Aguinaldo et al. – 2009 [29]	69 – C, PRO	50 ± 29	N/A	N/A
Solomito et al – 2015 [30]	99 – C	75.6 ± 15.3	N/A	N/A
Laughlin et al. – 2014 [32]	65 – C, PRO	N/A	SLAP – 87.8 ± 12.5 Control – 87.5 ± 17.8	N/A
Fleisig et al. – 2015 [33]	80 – PRO	UCL – 99 ± 17 Control - 99 ± 16	UCL - 101 ± 18 Control – 102 ± 17	UCL – 1250 ± 140 Control – 1280 ± 170
Luera et al. – 2018 [25]	77 – HS, PRO	HS – 50.43 ± 17.71 PRO – 86.35 ± 16.23	HS – 54.26 ± 18.21, PRO – 93.43 ± 16.59	HS – 612.20 ± 142.68, PRO – 1056.95 ± 134.27
Escamilla et al. – 2018 [26]	207 – PRO	OH – 97 ± 11 SA – 94 ± 16 3Q – 88 ± 12	OH – 98 ± 11 SA – 95 ± 16 3Q – 91 ± 12	OH – 1109 ± 141 SA – 1069 ± 141 3Q – 1129 ± 133

2.3.1 Quantifying Pitching Biomechanics

Some of the first motion analysis studies aimed to quantify the biomechanics of pitching, including kinematics and kinetics [15–17]. While qualitative descriptions of biomechanics existed, motion analysis allowed for accurate quantitative descriptions. Joint internal forces and torques, obtained via motion analysis and inverse kinematics, represent net forces acting upon a joint.

Figure 2.3 and 2.4 show the forces and torques in the elbow and shoulder joints throughout the pitching motion. At FC, the shoulder is externally rotating [15,17] and horizontal adduction torque is present in the shoulder [15,16]. Shortly after FC, abduction and IR torques begin in the shoulder, and varus torque in the elbow joint [15,16]. Just before MER, shoulder IR and elbow varus torques peak [15,16]. Just after MER, the shoulder begins to internally rotate, but is still in a position of ER overall at BR [15,17]. Horizontal abduction torque begins in the shoulder, and elbow flexion torque in the elbow [16]. After BR, the shoulder horizontally adducts and continues to internally rotate [17]. Shoulder and elbow compressive forces peak at this point, with shoulder compressive forces reaching up to 1090 N [16].

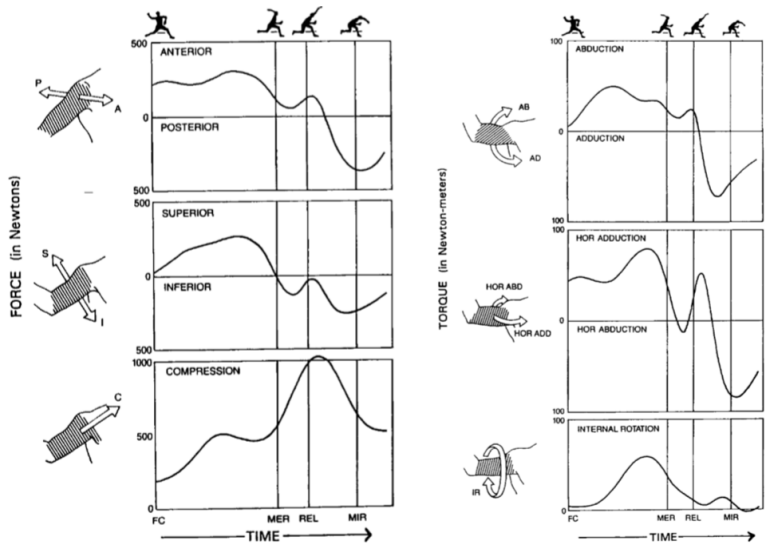

Figure 2.2: Forces and torques on the shoulder throughout the pitching motion (REL=BR) [16].

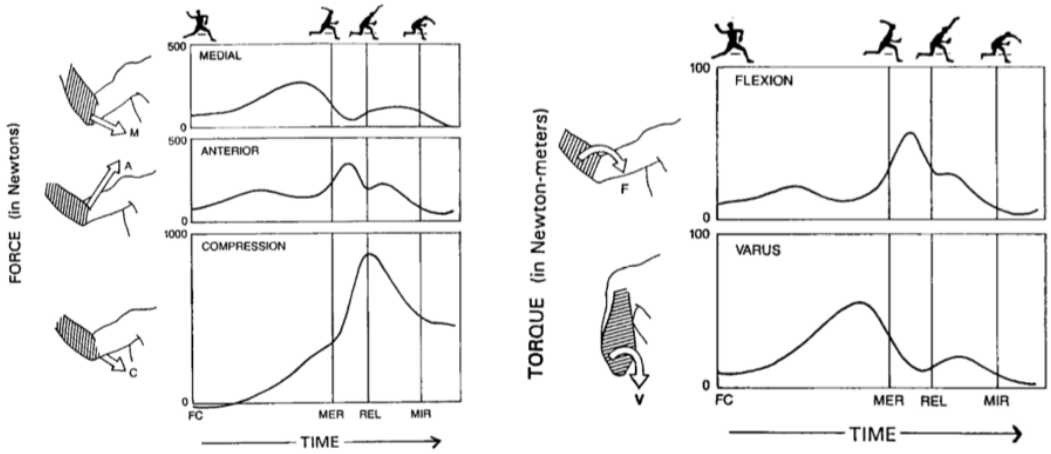

Figure 2.3: Forces and torques on the elbow throughout the pitching motion [16].

Quantifying the kinematics and kinetics of the pitching motion show that pitching is a highly dynamic motion that puts unique demands on the shoulder and elbow. This information can be used to draw conclusions about what is occurring during the pitching motion, when in the pitching motion injuries may occur, and how to avoid them. Peak torques occur just before MER for shoulder IR (67 Nm) and elbow varus torque (64 Nm)

[15,16]. The IR torque that resists ER may be transmitted through the humerus to the elbow joint, where a large varus torque is seen that stresses the UCL [15]. It is estimated that half of the varus torque at the elbow is placed on the UCL (34.6 Nm), which is above the maximum varus torque producible to failure in UCLs in cadaveric studies (32.1 Nm) [16]. Keeping elbow varus torque within a safe range is important to avoid injury to the UCL that often requires surgery and a lengthy recovery time.

At MER, the arm is can reach an angle of 180˚ ER [17]. The arm then undergoes rapid IR just after MER, and can reach velocities up to 7000 ˚/sec before BR [17]. Great care must be taken to prepare the shoulder for these intense demands. Defining, monitoring and maintaining proper shoulder rotational flexibility and strength may help pitchers to reduce injury risk to the shoulder. After BR, the shoulder muscles attempt to decelerate the arm and prevent distraction, horizontal adduction, and IR motion [16]. Compressive force and horizontal adduction torque at this point may be the primary cause of rotator cuff tears [16]. These conclusions are consistent with the electromyographic findings showing activity in the posterior shoulder muscles after BR, including the teres minor, infraspinatus, and posterior deltoid [34].

2.3.2 Pitching Biomechanics Correlations

Increasing pitch velocity without increasing joint loads to unsafe levels allow pitchers to improve in an efficient manner. Discovering correlations between biomechanics and other metrics of interest can help pitchers accomplish this. Multiple studies have investigated correlations between pitch velocity and biomechanics, with the primary goal of determining ways to increase pitch velocity and performance [27,30,35].

These results are outline in table 2.2. Correlations have been found between kinetic metrics and pitch velocity [27], timing of events and pitch velocity [27], and kinematic metrics and pitch velocity [27,30].

Table 2.2: Subject pool, purpose, and key findings of studies investigating correlations between key biomechanics (→ = correlated with, ↑ = increased, ↓ = decreased).

Study	Subjects	Purpose	Key Findings
Stodden et al. – 2005 [27]	19 – C	Investigate correlations between kinetic, temporal, and kinematic parameters on pitch velocity	• Elbow flexion torque, shoulder proximal force, elbow proximal force → ↑ pitch velocity • Increased time to maximum shoulder horizontal adduction and decreased time to maximum shoulder IR → ↑ pitch velocity • Decreased shoulder horizontal adduction at FC, decreased shoulder adduction during acceleration, increased trunk tilt at BR → ↑ pitch velocity
Aguinaldo et al. – 2009 [29]	69 – C, PRO	Investigate correlations between the onset of trunk rotation, other biomechanical variables with elbow valgus load	• Increased elbow flexion → ↓ elbow valgus torque • Early trunk rotation, maximum shoulder ER → ↑ elbow valgus torque • Sidearm delivery higher elbow valgus load than overhand
Solomito et al. – 2015 [30]	99 – C	Investigate correlations between contralateral trunk lean and ball velocity and kinetics at the elbow and shoulder joints	• Greatest contralateral trunk lean occurs at time of peak elbow varus torque • Contralateral trunk lean → ↑ pitch velocity • Contralateral trunk lean → ↑elbow varus torque, glenohumeral IR torque
Post et al. – 2015 [35]	67 – C	Investigate correlations between pitch velocity, key elbow and shoulder kinetics	• Shoulder distraction force → ↑ pitch velocity • No correlations between velocity and elbow valgus torque, shoulder ER torque

These findings may give some insight on how to increase pitch velocity and performance, as well as what kinetic loads on the body increase with pitch velocity. However, caution should be taken when prescribing changes to pitching mechanics. Solomito et al. found a positive correlation between pitch velocity and contralateral trunk lean at MER and BR, but a positive correlation was also found to elbow varus torque and glenohumeral IR torque [30]. For every 10˚ increase of the median contralateral trunk lean at MER, pitch velocity increased 1.1 miles per hour (1.5%), while elbow varus torque increased 3.7 Nm (4.8%) and IR torque by 2.5 Nm (3.2%) [30]. Therefore, while increasing contralateral trunk lean may improve pitch velocity, the additional risk in the form of higher torques on the arm may outweigh the benefits of prescribing this mechanical change to the pitching motion.

Stodden et al. postulated that the biceps brachii may play a critical role during pitching due to its biarticular nature allowing it to stabilize both the shoulder and elbow during pitching [27]. The biceps brachii provides elbow flexion torque, controls the rate of elbow extension, and enhances the effect of shoulder IR torque on the velocity of the hand during IR [16,27]. The biceps brachii also resists both distraction forces on the humerus and the forearm [27]. Without proper mechanics, the biceps brachii may undergo shoulder proximal force and elbow flexion torque simultaneously, resulting in overload [16,27]. EMG activity in the biceps is higher in pitchers with shoulder instability [36], and high forces on the biceps brachii may cause the labrum to tear [16]. Elbow flexion torque and shoulder proximal force are both correlated with pitch velocity, however simply aiming to increase them may not be the best approach. Close attention

should be paid to the timing of peak elbow flexion torque and shoulder proximal force during the pitching motion [27].

Correlations between kinematic and kinetic metrics are important to provide insight on what causes high forces and torques, and how to decrease them and reduce injury risk. Increased elbow flexion (at both the point of peak valgus torque and BR) was correlated with decreased elbow valgus torque [29]. Early trunk rotation and maximum shoulder ER were correlated with increased elbow valgus torque [29]. Sidearm pitchers were found to have increased elbow valgus torque compared to overhand throwers [29]. These results show that peak elbow valgus torque is related to the pitching mechanics of the elbow and shoulder and should be closely monitored.

Increasing pitch velocity without excessive joint load increases allow pitchers to efficiently improve performance without increasing risk of injury [29]. Investigating correlations between velocity, kinematics, and kinetics can give coaches and clinicians useful information on how to make changes to pitching biomechanics to accomplish this goal. Studies have found correlations between velocity and elbow flexion torque, shoulder proximal force, elbow proximal force, and contralateral trunk lean [27,30,35]. Increased elbow flexion, and later trunk rotation may decrease elbow valgus torque [29]. Caution and consideration must be given to increased joint loads and injury risk when prescribing changes to pitching form. More research must be done to further define correlations between pitch velocity, kinematics, and kinetics to aid in improving performance and decreasing injury risk.

2.3.3 Comparison of Populations, Parameters

Comparing the biomechanics of different populations and parameters is useful to understand cause and effect relationships, as well as alterations and compensations in mechanics. Several studies have investigated differences in pitching biomechanics of varying populations [25,26,28,31–33]. The results of these studies are outlined in table 2.3. Differences in biomechanics across levels of competition have been found [25,28,31]. Some studies have found professional pitchers are more efficient in certain aspects when compared to youth, high school, and college pitchers [25,28].

Table 2.3: Subject pool, purpose, and key findings of studies comparing biomechanics of various populations and parameters.

Study	Subjects	Purpose	Key Findings
Luera et al. – 2018 [25]	77 – HS, PRO	Compare pitch velocity, kinematics, kinetics of HS and PRO pitchers to identify differences, role in UCL injury	• HS pitchers experience high elbow varus torque relative to their body size compared to PRO pitchers • PRO pitchers may utilize forces generated by trunk rotation and pelvis better than HS pitchers
Escamilla et al. – 2018 [26]	207 – PRO	Compare biomechanics of overhand, 3-quarter, and sidearm pitchers	• Sidearm pitchers have less shoulder anterior force, greater elbow flexion torque and shoulder ER • Sidearm pitchers may be at greater risk for labral injury, less risk for shoulder joint capsule and rotator cuff injury
Aguinaldo et al. – 2007 [28]	38 – Y, HS, C, PRO	Effects of trunk rotation on shoulder rotational torques during pitching investigated across multiple levels	• PRO pitchers had lowest rotational torque among mature players, rotated trunks later in pitching cycle • Rotating trunk later optimal to decreased shoulder joint load by conserving momentum generated by trunk
Fleisig et al. – 2009 [31]	93 – Y, HS, C, PRO	Compare variability of pitching biomechanics within individuals at various levels of baseball	• Individual kinematics standard deviations greatest for youth pitchers, decreased for higher levels of competition • No significant differences in individuals in temporal or kinetic metrics across all levels
Laughlin et al. – 2014 [32]	65 – C, PRO	Evaluate biomechanics of pitchers with history SLAP tear, compare to control group	• SLAP pitchers less shoulder horizontal abduction, shoulder ER • SLAP pitchers more upright trunk, less forward trunk tilt at BR
Fleisig et al. – 2015 [33]	80 – PRO	Compare biomechanics of pitchers with history of UCL reconstruction to control group	• No significant differences in pitching biomechanics found between UCL reconstruction and control group

Professional pitchers may have more consistent and efficient mechanics than lower level pitcher. Significant differences were found between kinematics the standard

deviations of various levels of pitchers (youth, high school, college, minor league, major league) including front foot placement and front knee flexion at FC, maximum upper torso angular velocity, maximum elbow flexion, and maximum shoulder ER at arm cocking, and trunk forward tilt at BR [31]. A decrease in individual standard deviations of pitching kinematics indicates greater consistency of mechanics. Individual standard deviations for pitching kinematics were highest for youth pitchers, and tended decrease in higher levels [31]. Professional pitchers have displayed key kinetic and kinematic differences compared to lower levels of competition [25,28]. Kinetic differences include lower elbow varus torque normalized by height and weight (4.48 ± 0.63 Nm/H*BW) compared to high school pitchers (5.59 ± 0.81 Nm/H*BW) [25], and lower shoulder IR torque normalized to body weight and height (25 ± 3% BW*H) than college (43 ± 5% BW*H), high school (49% ± 5% BW*H), and youth (40 ± 3% BW*H) pitchers [28]. Kinematic differences include increased back hip and pelvis rotation at maximum knee height and hand separation compared to high school pitchers [25], and later trunk rotation (34.3% of pitch cycle) compared to youth (5.0%), high school (6.4%) and college (14.2%) [28].

Decreased standard deviations in higher levels of competition may provide coaching points of emphasis to improve performance. A pitcher must be able to pitch with velocity and location, among other things, to be successful and rise to higher levels of competition. High variability in foot placement and front knee flexion at FC may be easily correctable due to the slow, easily observable nature of the beginning of the pitching motion [31]. Decreasing variability in kinematics during more rapid phases of pitching such as maximum elbow flexion and maximum shoulder ER may be more

challenging, and may come with repetition and neuromuscular development [31]. Increased variability in forward trunk tilt at lower levels may result in inconsistent pitch velocity [31], which is in accordance with its correlation with pitch velocity [27]. More consistent mechanics may lead to increased performance in the form of both increased pitch velocity and ability to locate pitches [31].

The increased ability of professional pitchers to generate rotational forces and transfer them up the kinetic chain may explain their increased efficiency in the form of lower normalized elbow varus torque than high school pitchers [25]. High school pitchers may increase velocity by placing additional stress on the pitching arm, resulting in increased risk to injury [25]. Whereas professional pitchers are able to utilize their lower half keeping their back hip and pelvis back longer [25], and rotating their trunk later in the pitch cycle [28]. A focus on the rotational kinematics of the back hip, pelvis, and trunk may aid in increasing velocity and performance without increasing the relative torque on the elbow [25,28].

Some studies have compared the pitching biomechanics of different pitching arm slot styles, such as overhand, 3-quarter, and sidearm [26,29]. Sidearm pitchers have been found to have decreased shoulder anterior force [26], increased elbow flexion torque [26], increased ER angle [26], and increased elbow valgus torque [29]. However the study by Escamilla et al. found no significant differences in elbow varus torque between populations [26], contradicting the study by Aguinaldo et al. [29]. Results have varied, indicating pitching with different arm slots may have unique kinetic consequences on pitchers.

Grouping pitchers based on injury history and comparing biomechanics is important to identify possible compensatory and physiological changes resulting from specific injuries. Comparisons of the biomechanics of pitchers with a history of SLAP tears [32] and UCL tears [33] to control groups with no injury history have been performed. SLAP pitchers displayed decreased shoulder horizontal abduction at FC (10.0 ± 13.2 vs 21.0 ± 11.7), maximum shoulder ER (168.3 ± 12.7 vs 178.3 ± 7.3), and trunk forward tilt at BR (30.2 ± 6.3 vs 34.4 ± 6.6) than the control group [32]. These differences may aid in rehabilitation and coaching of pitchers returning from SLAP tears. No differences in pitching biomechanics were found between pitchers with previous UCL tears and the control group [33].

Comparing the biomechanics of different populations of pitchers such as level of competition, pitching style, and injury history gives useful insight into possible mechanical advantages, compensatory and physiological changes, rehabilitation methods, and coaching points of emphasis to improve performance and decrease injury risk. More research must be done to discover additional differences in pitching biomechanics between populations and parameters.

2.4 CLINICAL MEASURES OF STRENGTH AND FLEXIBILITY

2.4.1 Flexibility

The glenohumeral joint is a synovial ball-and-socket joint that undergoes extreme ROM during the pitching motion. The glenohumeral joint has three degrees of freedom: flexion/extension in the sagittal plane, abduction/adduction in the frontal plane, and IR/ER in the transverse plane [37]. Of interest is IR and ER because of the high angular

velocities and accelerations experienced during pitching. Numerous studies have shown a shift in ROM of the glenohumeral joint in pitchers, where ER gains flexibility, and IR loses flexibility [1–4]. This means that the D arm total ROM is similar to the ND arm but shifted externally (figure 2.7). All studies examined test the ROM with the shoulder in a position of 90˚ shoulder abduction and 90˚ elbow flexion.

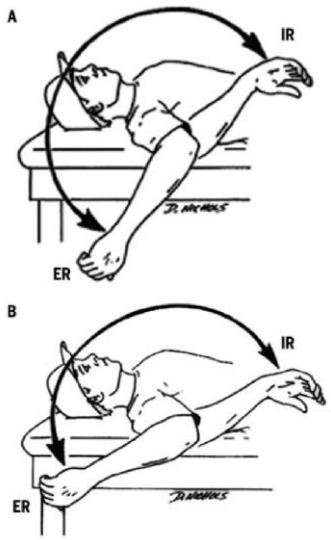

Figure 2.4: Glenohumeral total ROM in the D arm (A) and ND arm (B) showing a shift in total ROM externally in the D arm of pitchers [20].

Table 2.4 shows the glenohumeral ROM measures between arms of pitchers in various studies and levels of competition. Most studies show that the D and ND arms in pitchers have significant differences in glenohumeral rotational ROM. All studies showed significant differences in both IR and ER ROM [1–4]. Two studies also showed significant differences in total ROM [2,4]. The measured ROM varied greatly between the studies, with total ROMs ranging from 146.9 to 230˚.

Table 2.4: Comparison of glenohumeral ER and IR ROM studies (* indicates significant difference between D and ND arms) Values are means with standard deviations (if provided) in degrees.

Study	Subjects	D ER ROM	ND ER ROM	D IR ROM	ND IR ROM	D Total ROM	ND Total ROM
Brown et al. 1988 [1]	41 PRO	141 ± 14.7*	132 ± 14.6*	83 ± 13.9*	98 ± 13.2*	224	230
Hurd et al. 2011 [2]	210 HS	130 ± 11*	120 ± 10*	60 ± 11*	75 ± 11*	190 ± 15*	195 ± 15*
Anloague et al. 2012 [3]	42 C	98.92 ± 17.68*	84.94 ± 10.79	47.98 ± 9.88*	60.69 ± 8.27*	146.9	145.6
Wilk et al. 2015 [4]	296 PRO	131.2*	124.9*	52.3*	62.8*	183.4*	187.7*

Varying stabilization techniques utilized likely contribute to these differences. A study by Wilk et al. investigated IR ROM using three different stabilization techniques [38]. The three different methods include stabilization of the humeral head, stabilization of the scapula, and visual inspection without stabilization (figure 2.8). Significant differences in IR ROM were found between all three methods (no stabilization 58˚, scapular stabilization 46˚, humeral head stabilization 40˚) [38]. Of the studies summarized in table 2.4, one study did not report their stabilization technique [1], one utilized the humeral head stabilization method [2], and two utilized the scapular stabilization method [3,4]. Furthermore, three studies ensured the humerus was in the scapular plane [2–4] while one did not provide detail on the plane involved [1]. In summary, although the results between studies varied along with some methodology, all showed significant bilateral differences in glenohumeral rotational ROM.

Figure 2.5: Stabilization of humeral head (left), stabilization of scapula (middle) and visual inspection without stabilization (right) [38].

Studies have also investigated shoulder rotational ROM patterns in the D arm of pitchers over time [39–41]. Reinold et al. tested glenohumeral D and ND rotational motion before, immediately after, and 24 hours after pitching [39]. Table 2.5 displays their results. Changes were not apparent in the ND arm, with no significant differences before or after pitching for ER, IR, or total ROM [39].

Table 2.5: Glenohumeral ROM before, immediately after, and 24 hours after pitching in the D shoulder [40] (* indicates significant difference compared to ROM before pitching).

Shoulder, ROM	Before	After	24 Hours After
D ER	136.5 ± 9.8	135.3 ± 9.3	136.5 ± 9.0
D IR	54.1 ± 11.4	44.6 ± 11.9*	46.5 ± 10.0*
D TOTAL	190.6 ± 14.6	179.9 ± 13.7*	182.9 ± 11.5*

Dwelly et al. tested glenohumeral ROM in collegiate baseball players over the course of the season to examine changes in ROM over time [40]. Significant increases were observed in ER ROM from pre-fall to pre-spring, and pre-spring to post-spring [40]. Interestingly, these studies show effects on IR ROM acutely, but ER long term. However, it is important to note that the studies demographics were different, as Reinold et al. tested professional baseball pitchers while Dwelly et al. tested collegiate baseball and softball players, including nonpitchers. The study by Dwelly et al. also excluded players

who were injured during the season, and because GIRD (glenohumeral IR deficit) is correlated with shoulder injury [41], pitchers that may have shown IR decreases became injured and were excluded.

Wilk et al. measured glenohumeral rotational ROM on D and ND arms of pitchers over the course of three seasons and recorded days missed due to injury or surgery [41]. It was found that pitchers with GIRD (defined as at least 20˚ less IR in the D arm compared to the ND) were more likely to be injured than those without GIRD (28% vs. 17% injured) [41]. It was also found that 13% of pitchers with total ROM deficits of 5˚ or less were injured, while 27% of pitchers with greater than 5˚ of total ROM deficits were injured [41].

Throughout relevant literature, it is apparent that the demands of throwing alter the physiology of the tissue responsible for controlling the motion of the glenohumeral joint. Increases in ER ROM, decreases in IR ROM, or both in the D arm compared to the ND arm occur [1–4]. Both short and long term ROM differences result from pitching in individuals [39,40]. GIRD and total ROM losses have been linked to injury [41]. More research must be done on what the healthy glenohumeral rotation ROM range is, as well as what specific pitching metrics are altered by shifts in ROM. Determining correlations between shoulder flexibility and pitching biomechanics can help accomplish these tasks.

2.4.2 Isokinetic Strength

Isokinetic testing is useful in assessing the shoulder strength of pitchers. Dynamometers are isokinetic measurement devices used to measure IR and ER strength of the shoulder. Dynamometers can measure shoulder torques both eccentrically and

concentrically, and at different rotational velocities. Both arms are often tested and compared to provide insight on bilateral differences in physiology. In research involving isokinetic strength of baseball players, the arm is typically placed in a position of 90˚ shoulder abduction and 90˚ elbow flexion due to the similarity to the position of the arm during throwing. Many studies have been performed to examine the isokinetic parameters of the shoulders of baseball players and pitchers [5–12] (table 2.6).

Table 2.6: Comparison of isokinetic peak torque (Nm) in ER and IR at 90˚ shoulder abduction and 90˚ elbow flexion across various studies (Subj = subjects, vel. = velocity, * indicates significant difference between D and ND arm).

Study	Subj.	Vel. (˚/sec)	C ER (D, ND)	C IR (D, ND)	E ER (D, ND)	E IR (D, ND)	C ER/IR Ratio	E ER/IR Ratio
Ellenbecker et al. 1997 [5]	125 PRO	210	36.5 ± 6.8, 37.2 ± 6.1	106.9 ± 26.0, 98.4 ± 23.3*	-	-	0.67 ± 0.13, 0.74 ± 0.12	-
		300	35.7 ± 6.8, 35.8 ± 5.5	95.7 ± 24.4, 87.7± 21.6 *	-	-	0.70 ± 0.12, 0.78 ± 0.12	-
Mulligan et al. 2004 [6]	39 HS	90	9.45 ± 6.47, 9.91 ± 6.74	16.23 ± 11.02, 14.95 ± 10.18*	10.09 ± 4.41, 10.60 ± 9.22	16.65 ± 11.73, 15.40 ± 12.08	0.58 ± 0.16, 0.68 ± 0.15*	0.63 ± 0.16, 0.65 ± 0.24
		180	13.63 ± 9.87, 14.76 ± 10.49	20.70 ± 17.15, 20.47 ± 16.61	14.82 ± 11.43, 15.19 ± 10.71	19.14 ± 12.37, 18.82 ± 12.60	0.71 ± 0.18, 0.76 ± 0.21	0.77 ± 0.17, 0.83 ± 0.16
Hinton et al. 1988 [7]	26 HS	90	26.0 ± 5.2, 24.5 ± 5.4 *	40.5 ± 7.3, 35.1 ± 7.9 *	-	-	0.69 ± 0.10, 0.76 ± 0.10 *	-
		240	18.2 ± 5.0, 17.8 ± 4.7	29.0 ± 8.3, 25.8 ± 6.9 *	-	-	0.71 ± 0.14, 0.80 ± 0.11 *	-
Wilk et al. 1993 [8]	150 PRO	180	46.8 ± 8.4, 49.5 ± 9.2 *	73.1 ± 11.9, 71.0 ± 12.9	-	-	0.65 ± 0.09, 0.64 ± 0.11	-

		300	39.7 ± 6.9, 40.8 ± 8.5	66.4 ± 11.5, 65.1 ± 14.1	-	-	0.61 ± 0.10, 0.70 ± 0.13	-
Alderink et al. 1986 [9]	24 HS/C	90	35.7 ± 8.1, 36.3 ± 7.5	53.0 ± 10.6, 52.1 ± 9.9	-	-	0.66 ± 0.09, 0.70 ± 0.09	-
		120	34.0 ± 7.2, 35.3 ± 6.9	50.6 ± 9.6, 49.1 ± 9.5	-	-	0.68 ± 0.10, 0.72 ± 0.07	-
		210	31.9 ± 5.8, 34.2 ± 6.0 *	45.0 ± 8.5, 45.0 ± 8.7	-	-	0.71 ± 0.19, 0.76 ± 0.09	-
		300	30.0 ± 6.0, 32.0 ± 6.2 *	43.0 ± 8.8, 42.4 ± 8.5	-	-	0.70 ± 0.08, 0.76 ± 0.11	-
Sirota et al. 1997 [10]	25 PRO	60	66.2 ± 18.0, 59.9 ± 15.5	70.0 ± 20.5, 70.9 ± 16.7	73.9 ± 21.2, 68.6 ± 15.7	81.2 ± 22.5, 79.2 ± 21.3	0.98 ± 0.31, 0.85 ± 0.17	0.93 ± 0.23, 0.89 ± 0.17
		120	58.8 ± 15.6, 56.7 ± 13.8	64.1 ± 18.2, 64.3 ± 15.0	76.5 ± 18.0, 75.4 ± 16.5	84.5 ± 21.2, 81.5 ± 20.6	0.97 ± 0.34, 0.91 ± 0.21	0.92 ± 0.15, 0.95 ± 0.17
Mikesky et al. 1995 [11]	25 C	90	62.1 ± 3.1, 60.7 ± 2.8	96.3 ± 8.9, 88.0 ± 7.2	66.6 ± 3.1, 69.9 ± 3.8	96.5 ± 8.3, 93.2 ± 6.9	0.69 ± 0.05, 0.76 ± 0.05	0.80 ± 0.07, 0.81 ± 0.06
		210	54.6 ± 2.7, 55.0 ± 3.0	85.8 ± 7.5, 82.6 ± 6.1	64.9 ± 3.5, 67.9 ± 3.5	102.1 ± 7.5, 98.2 ± 6.2	0.71 ± 0.05, 0.76 ± 0.07	0.72 ± 0.06, 0.74 ± 0.05
		300	53.2 ± 2.8, 50.3 ± 2.8	84.0 ± 7.7, 80.1 ± 6.4	63.0 ± 3.1, 65.8 ± 3.4	108.7 ± 6.8, 102.5 ± 6.6	0.72 ± 0.05, 0.75 ± 0.09	0.62 ± 0.04, 0.70 ± 0.06
Noffal et al. 2003 [12]	16 C	300	30.8 ± 4.8, 30.5 ± 4.6	48.4 ± 9.6, 42.1 ± 7.1	55.0 ± 6.6, 61.1 ± 7.3	71.8 ± 9.4, 59.7 ± 11.6	0.65 ± 0.08, 0.73 ± 0.09	-

2.4.2.1 Concentric Strength

Several studies have compared isokinetic concentric measures of the D and ND arm (table 2.6) [5–10]. Some found statistically significant differences between D and ND arm ER torque [7–9]. Two studies found ER torque lower in the D arm compared to the ND arm, at 180 ˚/sec [8] and at 210 and 300 ˚/sec [9]. Multiple studies found a statistically significant difference in isokinetic IR torque between the D and ND arm [5–7]. The D arm had higher IR torque than the ND arm in each study, at various rotational velocities: 90˚/sec [6,7], 210 and 300˚/sec [5]. Only one found no statistically significant differences between rotational torques in either ER or IR between the D and ND limbs [10].

When comparing results across multiple studies, it is important to note the differences in methodology. The subject populations ranged from HS to PRO baseball pitchers. As expected, peak torques increased with level of competition. All the torque data in table 2.6 was taken with the arm at a position of 90˚ shoulder abduction and 90˚ elbow flexion. Sirota et al. reported mean torques of IR and ER [10], while all other studies considered reported mean peak torques [5–9]. Finally, different dynamometers were used across studies, including Cybex [5,9], Kin-Com [6,10], HUMAC [7], Biodex [8]. Caution must be used when comparing results obtained from different dynamometer systems.

2.4.2.2 Eccentric Strength

Some studies have tested eccentric rotational strength (table 2.6) [6,10–12]. No statistically significant differences were found between the D and ND eccentric mean

peak torque [6,10,11]. Noffal et. al did not perform statistical analysis to examine differences in eccentric torque between arms [12]. Populations ranged from HS to PRO, and test velocities from 60 to 300˚/sec. While not with significance, most D arm eccentric ER was lower than the ND arm [6,11,12], with the exception of the study by Sirota et al. [10]. D arm eccentric IR was higher in the D arm in all studies and test velocities, but also without significance [6,10–12].

The absence of significant differences between arms in eccentric torque production is counterintuitive, as the D arm ER musculature is subjected to eccentric loads during the deceleration phase of the pitching motion. Because of this, it would be reasonable to expect the D arm to have significantly higher eccentric ER torque than the ND arm. This was not the case in any of the studies reviewed [6,10–12]. Conversely, one could also expect D arm eccentric ER to be lower than the ND arm because of concentric ER bilateral differences [8,9], but this was not the case.

2.4.2.3 Isokinetic Torque ER/IR Ratios

ER/IR ratios are useful to quantify the balance between the rotator muscles of the shoulder. ER/IR ratios can be compared between arms to discover the physiological changes that pitching causes in the shoulder. If the D arm has increases in strength in one rotational direction without concurrent increases in the strength in the opposite direction, an imbalance is will develop, and the ER/IR ratio will differ from that of the ND arm.

For concentric strength ratios, two studies found significant differences between arms, with the D arm ratio lower than the ND [6,7]. Others did not perform statistical analysis to determine if significant differences were present between arms, but also

showed a lower concentric ER/IR ratio in the D arm compared to the ND [5,9]. Four studies found no significant difference between concentric ER/IR ratios at any velocity [8,10–12]. All studies displayed the trend of lower D arm ratios, except for Sirota et al., which showed the D arm ratios higher than all the ND arm at all velocities [10]. Three studies also compared the D and ND eccentric ER/IR ratio [6,10,11]. Although there were not significant differences between the D and ND arm ratios, all showed a trend of lower ratios in the D arm than the ND.

One study was unique in calculating a "functional" eccentric ER/concentric IR ratio [12]. This ratio may be more relevant to pitching because of the specific demands placed on the shoulder during pitching. These ratios were higher than the concentric ER/concentric IR due to the eccentric ER contractions producing higher torques. The functional ratio of the D arm was lower than that of the ND arm (1.17 ± 0.20 vs 1.48 ± 0.22), however statistical analysis was not run [12].

2.4.3 Isometric Strength

Isometric testing is another method of measuring the shoulder strength of baseball pitchers. Isometric testing involves utilizing a stationary dynamometer to measure isometric contraction strength of the shoulder. The muscle fibers remain the same length throughout an isometric contraction. More isokinetic glenohumeral rotation strength studies have been performed due to the dynamic nature of the pitching motion. However smaller and less expensive handheld dynamometers used to measure isometric strength may be more accessible.

Studies have shown the IR strength of the D arm significantly greater than the ND arm, while the ER strength of the D arm was significantly lower than the ND arm [14,42]. Decreased preseason isometric strength has also been linked to injury in professional pitchers [43]. Over a 5-year period, an association between prone ER and prone ER/IR ratio to injury and injury requiring surgery, as well as prone IR to injury requiring surgery was found [43]. The positions of all three isometric studies differed, with one laying supine with the arm at 90˚ shoulder abduction and elbow flexion, and 0˚ ER [14], one seated and upright, with 90˚ shoulder abduction and elbow flexion, and 45˚ ER [42], and one laying prone at 90˚ shoulder abduction and elbow flexion, and 0˚ ER. The position of the arm in ER is particularly important for measuring isometric strength. If the arm is in ER, the muscles responsible for ER are shortened, decreasing their force production capabilities. Conversely, if IR is tested in a position of ER, they will be stretched, resulting in increased passive tension and total force production.

Isometric testing has shown similar results as isokinetic testing and appears to also be an effective way to measure glenohumeral rotational strength in pitchers. Attention must be minded to the arm positioning, particularly in ER when comparing strength data across studies. Isokinetic testing may be more valuable due to the dynamic nature of the pitching motion, and ability to analyze concentric and eccentric data.

2.4.4 Grip Strength

Limited research has been done on correlations between grip strength and clinical or biomechanical metrics. Extrinsic hand flexors and extensors both contribute to grip strength. Flexor muscles crossing the metacarpophalangeal and proximal and distal

interphalangeal joints contract to close the hand, while the extensor muscles neutralize the flexion action at the radiocarpal joint and place it in slight extension to lengthen the flexion muscles.

Studies have shown grip strength is significantly higher in the D than the ND hand of baseball players [44,45]. However this may be common for non-baseball players as well, as Jarit et al. found no significant differences between D/ND grip strength ratios of baseball players and a control group [45]. Studies have shown that D hand grip strength is not significantly different from pregame to postgame in collegiate starting pitchers [46], or in duration of career in semiprofessional pitchers [47]. One study found a slight relationship between elbow injuries and D hand grip strengths of 25 kg or more in youth baseball players, but without statistical significance [48]. The same study also found no relationship between D/ND grip strength ratio and elbow injuries [48]. Wrist extension may also contribute to pitching. Pedegana et al. found a strong correlation was found between wrist extension and pitch velocity [49]. However, these results were contradicted by Bartlett et al., who found no correlations between wrist extension or wrist flexion and pitch velocity [50].

More research must be done on grip strength of baseball players, specifically pitchers. The flexor-pronator group of muscles, originating from the medial epicondyle (pronator teres, flexor carpi radialis, flexor carpi ulnaris, palmaris longus, flexor digitorum superficialis) provide dynamic support to valgus stresses on the elbow [21]. Injuries and weakness to this group of muscles may be a precursor for UCL injury. Identifying healthy grip strength ranges, ratios, and correlations to biomechanics of pitching may be helpful decrease risk of elbow injury in pitchers.

2.5 CORRELATIONS BETWEEN BIOMECHANICS AND CLINICAL MEASURES

Finding correlations between clinical measures of shoulder rotational strength and flexibility and biomechanics of the pitching motion may be useful for preventing injury and maximizing performance. Determining healthy ratios of ER/IR strength and flexibility can be accomplished by determining what ratios are linked to normal kinetics, and what ratios are linked to abnormally high kinetics. Exploring both concentric and eccentric contractions is valuable because both are required of the shoulder during pitching.

Some correlations including clinical measures that have been investigated include arm strength and flexibility and biomechanics [13], arm strength and velocity [50,51], and arm strength and injury [43]. No correlation was found between isokinetic ER or IR at 90˚/sec and pitch velocity [50]. Correlations were found between isometric IR and concentric elbow extension PT/BW and velocity [51]. A negative correlation was found between isometric ER strength and likelihood of injury requiring surgical intervention. A negative correlation was also found between ER/IR ratios and incidence of any shoulder injury [43]. Future research should continue to focus on investigating correlations between shoulder rotational strength and velocity and injury.

There has been only one study to our knowledge that has found correlations between clinical measures of strength and flexibility and biomechanics of pitching. Hurd et al. measured isometric IR and ER strength and pitching biomechanics of high school baseball pitchers to evaluate correlations between the measures [13]. The study found an inverse correlation between ER ROM and elbow adduction (varus) moment, and ER ROM and peak shoulder IR moment (figure 2.10) [13]. They also found a positive

correlation between isometric IR strength and peak shoulder ER moment, and peak elbow adduction moment and peak shoulder IR moment (figure 2.11) [13]. The study demonstrated that correlations exist between biomechanical measures and clinical strength measures. The results indicate that as the IR muscles strengthen, more torque is placed on the ER musculature during pitching. It also indicates that increasing ER ROM may elbow adduction and shoulder IR moment.

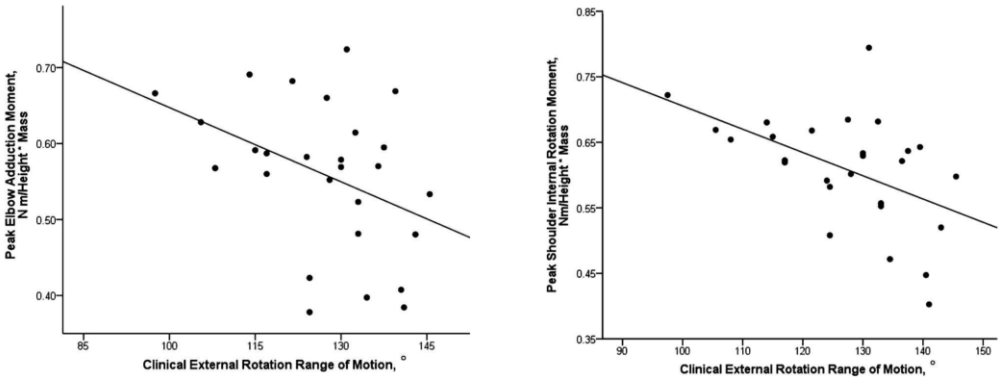

Figure 2.6: Correlations between clinical ER ROM and peak elbow adduction moment (left), and peak shoulder IR moment (right) [13].

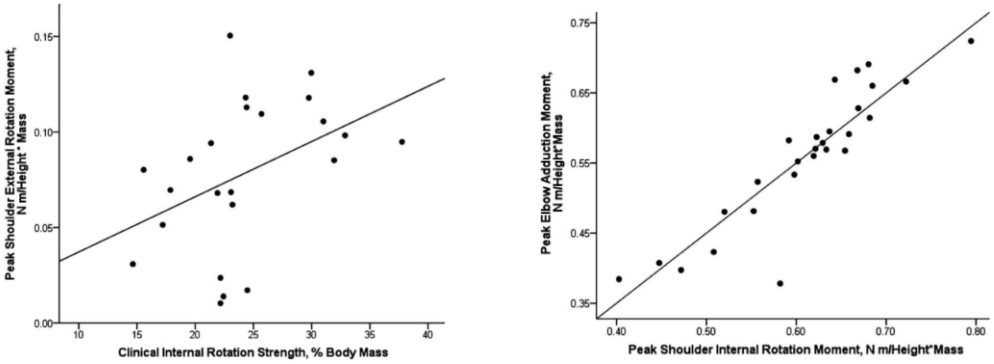

Figure 2.7: Correlations between peak shoulder ER moment and clinical IR strength (left), and peak elbow adduction moment and peak shoulder IR moment (right) [13].

These findings give potential solutions to decreasing high kinetics. More studies exploring correlations between clinical measures and pitching biomechanics are needed to discover additional relationships as well as verify those found by Hurd et al. The study findings may be limited by only using high school pitchers and only performing isometric strength testing [13]. Isokinetic strength may be more applicable due to the dynamic nature of the pitching motion. Due to differences found in pitching kinetics between skill level [25,28,31] and differences in strength ratios of various levels [6,7] the correlations found by Hurd et al. may not apply to all levels of pitchers. Determining these correlations will make biomechanical pitching analyses and strength and flexibility tests more interchangeable. If ER/IR strength ratios are correlated to a kinetic metric, then strength tests can be performed instead of a biomechanical analysis when they aren't available. Training with the goal of altering a strength ratio could become a method for improving poor kinetics. Our study aims to increase the understanding of the correlations that exist between pitching biomechanics and shoulder strength and flexibility ratios to offer solutions to reduce injuries and improve performance.

Correlations can be used to create predictive NNs. Limited research has been conducted to determine the use of NNs in the sports setting. Kipp et al. created a nonlinear autoregressive network to predict hip, knee, and ankle joint torques during a Olympic lift [52]. The inputs were the mass of the barbell and the vertical and horizontal positions of the barbell. The joint torques were predicted within 6% of the actual torques, measured via standard inverse dynamics [52]. This study showed that NNs can be used to predict kinetics using easily measured inputs.

No study to our knowledge has used NNs to predict kinetics using known correlations to clinical measures. This would be useful because clinical measures are more readily measurable than kinetics via motion analysis and inverse dynamics. If NNs can accurately predict kinetics using clinical strength measures, estimates can be made with convenience.

CHAPTER 3: METHODS

3.1 SUBJECTS

Twelve subjects (n=12, age: 21.0 years ± 2.4, height: 184.1 cm ± 7.5, and weight: 90.4 kg ± 14.0, 9 right handed, 3 left handed) participated in both test sessions and were included in statistical analysis. To be included in the study, subjects were required to be college age pitchers able to throw 10 fastballs during a testing session. Subjects with injuries in the previous twelve months or with prior shoulder or elbow surgery on the throwing arm were excluded from the study. Recruitment was performed by contacting coaches and managers of local collegiate teams and requesting pitcher participation. This study was approved by the MCW Institutional Review Board. Written informed consent was obtained prior to study procedures (Appendix A). Subjects underwent two testing sessions: clinical measurement and 3D motion analysis testing. A minimum of two days between clinical measurements and motion analysis was required to ensure maximal effort for both tests.

3.2 TEST PROTOCOL

3.2.1 Clinical Strength and ROM Testing

Passive ROM, grip strength, isokinetic shoulder strength, and isometric shoulder strength data was obtained during the clinical measures testing session. Anthropometric measurements recorded included height and weight. The subject underwent a standardized warm-up that included static and dynamic bilateral stretches. The static

warmup included overhead triceps, arm-across deltoid, and forearm wrist flexion and extension. All static stretches were held for ten seconds. The dynamic warmup included jumping jacks, arm circles forwards and backwards, and band-exercises of ten reps each including flies, reverse flies, and IR and ER rotation at zero- and ninety-degrees shoulder abduction. These stretches were chosen because they involve all the muscles being used during strength testing and are common to baseball pitching warmups. Dynamic stretches also helped prepare the subject for the dynamic nature of the isokinetic testing. The jumping jacks were performed first to elevate the heart rate, followed by the static stretches, and concluding with the dynamic stretches. After completion of the warmup, the subjects could do any additional stretches desired. Next, the passive shoulder ER and IR ROMs were measured before the strength test to ensure the absence of fatigue.

3.2.1.1 Passive Range of Motion Testing

Passive shoulder ER and IR ROM was measured with the subject laying supine on an exam table with the arm at 90° shoulder abduction, in the scapular plane, and 90° elbow flexion. The scapular stabilization method was utilized because it is the most clinically relevant glenohumeral ROM measurement techniques [38] (figure 3.1). The scapula was stabilized by applying pressure to the coracoid process and the spine of the scapula, while allowing normal glenohumeral motion [38]. This method allowed the end of the ROM of the glenohumeral joint to be determined as when the scapula begins to tilt. The glenohumeral joint was not stabilized to allow for normal glenohumeral arthrokinematics [38]. A rolled towel was placed under the shoulder parallel with the humerus to align the humerus with the scapular plane. A goniometer with a bubble level

(Jamar E-Z Read, Cedarburg WI) was used to ensure proper alignment in reference to the ground. The axis of the goniometer was placed over the olecranon process, with one line perpendicular the ground and the other line parallel with the ulna and ulnar styloid process, consistent with methods described by Wilk et al. [41].

The same two investigators tested ROM for all subjects, performing the same role each time. One investigator stabilized the arm and moved it through the rotation, while the other investigator measured the ROM using the goniometer. The right arm was measured first, followed by the left arm. Two measurements of ER followed by two IR were taken for each limb. The subject was instructed to indicate when they felt the end of their ROM was reached for safety purposes. Subject feedback along with the beginning of scapular tilt were used to determine the ROM. The average of the two measurements was recorded for each rotation direction and arm.

Figure 3.1: Shoulder Rotational ROM testing using the scapular stabilization method.

3.2.1.2 Grip Strength Testing

Grip strength was measured next using a digital handheld dynamometer (Jamar Plus+, Cedarburg, WI). The depth of the dynamometer handle was adjusted to so that the subject felt comfortable gripping it. The subject was seated with their arm at their side, 90° elbow flexion, 0-30° wrist extension and 0-15° ulnar deviation, and 0° of pronation-supination (figure 3.2). This position was chosen because it is the natural gripping position of the wrist and arm, and is consistent with relevant literature [53]. Three repetitions, each lasting three seconds in duration were performed for each hand, starting with the right hand. The subject was instructed to squeeze the handle with maximum effort for three seconds, pausing for ten seconds before moving on to the next repetition. The peak force of each trial, mean, and standard deviation were recorded.

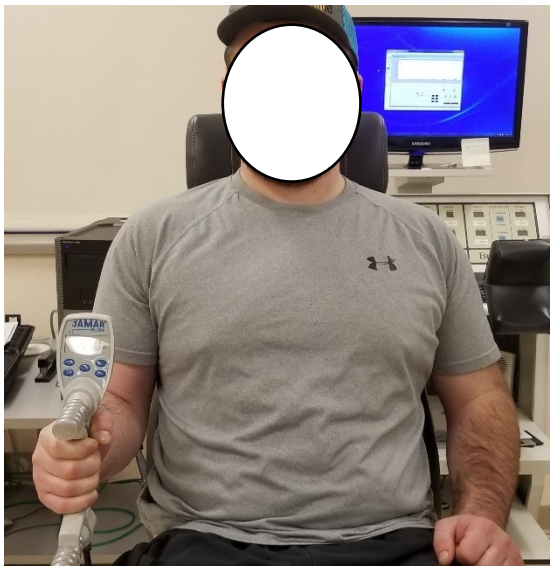

Figure 3.2: Grip strength testing position.

3.2.1.3 Isokinetic Strength Testing

Next, isokinetic shoulder strength testing was performed using a Biodex 3 dynamometer (Biodex Corp., Shirley, NY). The Biodex was calibrated according to user manual instructions before each subject was tested. The procedures of each strength test were explained to the subject before each round of testing. The subject was secured by chest and waste straps with their arm positioned at 90° of shoulder abduction and elbow flexion, and 30˚ of horizontal shoulder abduction to place the arm in the scapular plane, in accordance with previous studies [5–12].

The order of testing was isokinetic ER followed by IR, then isometric testing in both directions. A flow chart representation of the strength testing can be seen in figure 3.3. The subject was given a thirty-second rest period between tests in the same rotation direction, and a two-minute break between different test sets. All tests were performed for the ND arm before switching to the D arm. The subject was allowed additional time to stretch if desired after all tests were completed for the first arm. Both isokinetic ER and IR tests alternated between concentric and eccentric contractions, with five reps performed in each direction. Five repetitions were determined to be adequate in accordance with a study performed by Arrigo et al., which determined that during isokinetic testing of shoulder rotation strength, the peak torque and maximal work repetitions both occur most often between the 2nd and 4th test repetition [54]. The isokinetic testing velocity order was 90, 180, and 270 °/sec, consistent with previous methods [5–12]. All three velocities were tested for ER, followed by all three speeds for IR.

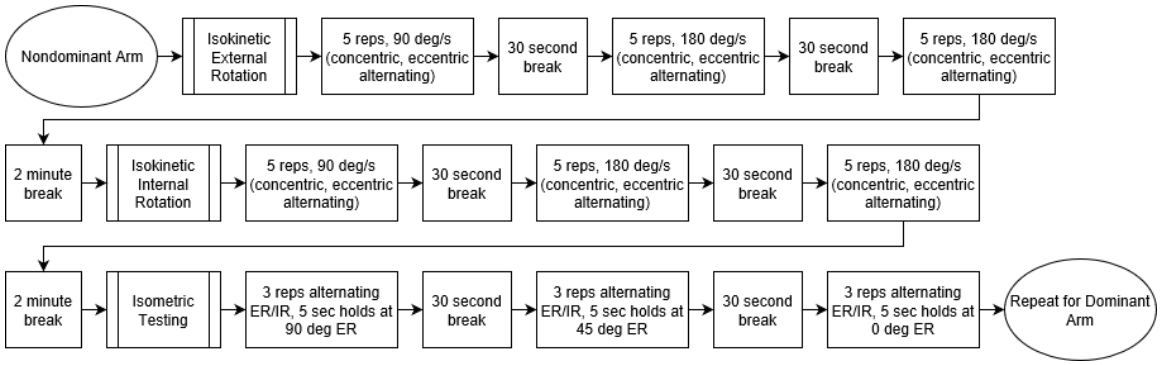

Figure 3.3: Flowchart of isokinetic and isometric strength testing procedures.

3.2.1.4 Isometric Strength Testing

After isokinetic tests were completed for one arm, the isometric test was performed. Alternating ER and IR isometric strength was measured in the same position of 90˚ of shoulder abduction and elbow flexion, at 0, 45, and 90° of ER (figure 3.4). Three repetitions, each lasting five seconds in duration were obtained in each rotational direction before moving on to the next testing position. The final isometric test concluded the strength testing for one limb before the opposite arm was tested in the same manner using both isokinetic and isometric protocols. The subject could perform additional arm stretches if desired before testing the opposite arm.

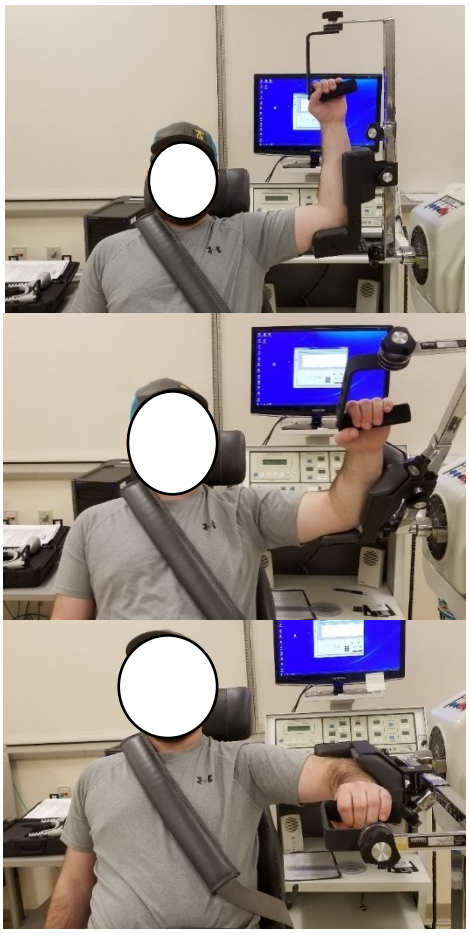

Figure 3.4: Shoulder rotational strength testing. Top to bottom: positions for isometric testing of 90, 45, and 0˚ ER. Isokinetic testing consisted of the full 90˚.

3.2.2 Motion Analysis Testing Session

The second testing session involved a 3D biomechanical pitching analysis. A system of eight Raptor-E cameras (Motion Analysis Corporation, Santa Rosa, CA) was positioned around an artificial mound to capture the motion of pitchers at 300 frames per second. Subjects stretched and warmed up as they normally would before pitching. A treadmill and elastic bands were provided if necessary. The subjects played catch in the lab to warmup. Forty-seven reflective markers (12.5 mm diameter) were attached to the subjects at specific locations: five markers on the hat (front, rear, both sides, and top of

head), sterno-clavicular process, xiphoid process, C7 and T10 spinous processes, dorsal side of D hand's 3rd metacarpal mid-point, dorsal side of the glove mid-base, and bilaterally the posterior superior iliac spine (PSIS), anterior superior iliac spine (ASIS), superior tip of acromion process, lateral portion of mid-bicep, medial and lateral epicondyles of the humerus, posterior portion of mid-forearm, styloid processes of the radius and ulna, greater trochanter, lateral mid-thigh, lateral and medial femoral condyles, lateral mid-shank, lateral and medial malleolus, dorsal midpoint of 3rd metatarsal, and calcaneus (figure 3.5).

Once the subjects were warmed up and markers applied, a static trial was recorded with the subject standing on the mound, with arms at 90˚shoulder abduction, elbow flexion, and IR. Ten fastball pitches were recorded, via either windup or stretch depending on the preference of the subject. Pitches were thrown into a net with a strike zone, which was used to record the location of each pitch. Velocity was recorded using a Stalker Sport 2 radar gun (Stalker Sports Radar, Richardson, TX) set up directly behind homeplate and the netting. Homeplate was positioned 60.5 feet from the pitching rubber.

Figure 3.5: Subject after all markers are placed on anatomical landmarks.

3.3 DATA PROCESSING

3.3.1 Clinical Measures Data

Averages and standard deviations were calculated for ER and IR passive ROM for both shoulders, and for grip strength of each hand. For the isokinetic testing at all three velocities, peak torque, peak torque normalized to body weight, work normalized to body weight, and total work were recorded bilaterally. Concentric ER/IR ratio, eccentric ER/IR ratio, and eccentric ER/concentric IR ratio were calculated. For isometric testing at all

three positions, bilateral peak torque and peak torque normalized to body weight were recorded. ER/IR isometric ratios were calculated.

3.3.2 Motion Analysis Data

Marker data was identified in Cortex software (Motion Analysis Corporation, Santa Rosa, CA) for static and pitching trials, and then exported into Visual 3D software (C-Motion, Germantown, MD) to be processed using a full body biomechanical model previously developed in the MCW Sports Medicine Lab [55,56].

3.3.2.1 Cortex Processing

The static trial was processed first. In a frame with all 47 markers visible, markers were identified, the trial was trimmed to one frame, and the coordinate 3D (C3D) file of the marker positions was exported. Three pitches of different velocities, including the top or near top velocity pitch were selected to be processed. Different velocities were used so that the game velocity torques could be interpolated. Pitches within or near the strike zone were used when possible. All markers were identified during the frames of interest, which began as the lead leg was lifted for the stride and ended after completion of the deceleration phase.

Once all markers were identified for as much of the frames of interest as possible, virtual and cubic join were used to fill in the remaining gaps. Cubic join fills in the gaps using a cubic spline. Virtual join uses the locations of three adjacent markers to create a virtual marker to fill the gap. The trial was then filtered using a low-pass Butterworth filter (13.4 Hz), virtual joint centers calculated, and exported as a C3D file. A template

was created to fit to the other dynamic trials to expedite the marker identification process. This procedure was repeated for the remaining two trials to conclude the Cortex processing.

3.3.2.2 Visual 3D Processing

The four C3D files, including one static trial and three pitches, were imported into Visual 3D for processing. Calculations were performed on a biomechanical model built in Visual 3D. The six basic steps to process data captured via motion analysis in Visual 3D are: 1. Creating a model using a static trial, 2. Associating data from dynamic trials to model, 3. Performing signal and event processing, 4. Defining kinematic and kinetic calculations, 5. Generating a report of the kinematics and kinetics, and 6. Exporting data for additional analysis [57].

The static trial with the subject standing in the modified T-position was used to create the model. Descriptions of the segment details and their local coordinate systems (LCS) are provided in table 3.1. Body segments included pelvis, thighs, shanks, feet, thorax, upper arms, forearms, hands, and head. Segments were defined in Visual 3D using the proximal and distal joints and radius. Joints were defined using lateral or medial markers, or joint centers. If lateral or medial markers were used to define the segment end, markers were directly used. Joint centers were calculated as half the distance between a lateral and medial markers. The radii of segment ends were also calculated as half the distance between lateral and medial markers. Additional markers on the segment that were not used to define it were selected as tracking markers. The LCSs were defined using a series of unit vectors. The $\vec{k}$ vector was always along the long axis of the bone.

An intermediate $\vec{v}$ vector, usually from the medial to the lateral marker at the distal end of the segment, and vector cross products were used to define the remaining $\vec{\imath}$ and $\vec{\jmath}$ vectors and an orthogonal LCS [58].

Table 3.1: Descriptions of the LCS used for each segment in the pitching model. R+L=right and left, L=lateral, M=medial, JC=joint center, F+R=front and rear.

Segment	Segment Mass (%), Geometry	LCS Origin	Defining Markers	Defining Landmarks	Tracking Markers	LCS Description
Pelvis	14.2%, Cylinder	Mid Iliac	N/A	R+L Iliac, R+L Hip	R+L ASIS, R+L PSIS	$\vec{k}$: Mid Hip to Mid Iliac $\vec{v}$: Left Hip to Right Hip $\vec{\jmath}$: $\vec{k}\ x\ \vec{v}$ $\vec{\imath}$: $\vec{\jmath}\ x\ \vec{k}$
Thigh	10%, Cone	Hip	L Knee	Hip JC, Knee JC	M Knee, Thigh, Trochanter	$\vec{k}$: Knee JC to Hip $\vec{v}$: M Knee to L Knee J: k x v $\vec{\imath}$: $\vec{\jmath}\ x\ \vec{k}$
Shank	4.65%, Cone	Knee JC	L Ankle	Knee JC, Ankle JC	M Ankle, L Knee, M Knee, Shank	$\vec{k}$: Ankle JC to Knee JC $\vec{v}$: M Ankle to L Ankle $\vec{\jmath}$: $\vec{k}\ x\ \vec{v}$ $\vec{\imath}$: $\vec{\jmath}\ x\ \vec{k}$
Foot	1.45%, Cone	Ankle JC	Toe, L Ankle	Ankle JC	M Ankle, Heel	$\vec{k}$: Toe to Ankle JC $\vec{v}$: M Ankle to L Ankle $\vec{\jmath}$: $\vec{k}\ x\ \vec{v}$ $\vec{\imath}$: $\vec{\jmath}\ x\ \vec{k}$
Thorax/ Abdomen	35.5%, Cylinder	Pelvis JC	N/A	Pelvis JC, Neck JC, Mid Neck	C7, T10, Sternum, Xiphoid	$\vec{k}$: Pelvis JC to Mid Neck $\vec{v}$: M Thorax to Mid Neck $\vec{\jmath}$: $\vec{k}\ x\ \vec{v}$ $\vec{\imath}$: $\vec{\jmath}\ x\ \vec{k}$
Upper Arm	2.8%, Cone	Shoulder JC	L Elbow	Shoulder JC, Elbow JC	M Elbow, Shoulder	$\vec{k}$: Elbow JC to Shoulder JC $\vec{v}$: M Elbow to L Elbow

						$\vec{j}$: $\vec{k}$ x $\vec{v}$ $\vec{\imath}$: $\vec{j}$ x $\vec{k}$
Forearm	1.6%, Cone	Elbow JC	L Elbow	Elbow JC, Wrist JC	M Elbow, M Wrist, L Wrist	$\vec{k}$: Wrist JC to Elbow JC $\vec{v}$: M Wrist to L Wrist $\vec{j}$: $\vec{k}$ x $\vec{v}$ $\vec{\imath}$: $\vec{j}$ x $\vec{k}$
Hand	0.6%, Sphere	Wrist JC	L Wrist	Wrist JC, Hand JC	M Wrist, Hand	$\vec{k}$: Hand JC to Wrist JC $\vec{v}$: Wrist JC to L Wrist $\vec{j}$: $\vec{k}$ x $\vec{v}$ $\vec{\imath}$: $\vec{j}$ x $\vec{k}$
Head	8.1%, Ellipsoid	Mid Neck	R Ear	Mid Neck, Mid Head	Top Head, F+R Head, R+L Ear	$\vec{k}$: Mid Head to Mid Neck $\vec{v}$: Mid head to R Ear $\vec{j}$: $\vec{k}$ x $\vec{v}$ $\vec{\imath}$: $\vec{j}$ x $\vec{k}$

Segment mass was calculated using predetermined proportions of the subject mass. Segment lengths were calculated using distances between proximal and distal markers or joint centers. The segment mass and geometry were used to compute inertial values. No constraints were placed on segments, and all degrees of freedom were permitted.

Once the model was created and applied to the static trial, the pitching trials were then associated with the model. This applied the created model and defined segments and LCS to the dynamic pitching trials. With the model now created and applied to all trials of interest, calculations including event detection, kinematics and kinetics were performed.

3.3.2.2.1 Kinematic Metrics

Kinematic metrics calculated included joint angles and joint and segment velocities and accelerations. Joint angles were calculated in Visual3D using Cardan angles. Three segment orientation matrices for X, Y, and Z were calculated and multiplied together to obtain a decomposition matrix. This provided the orientation of a segment LCS with respect to the global coordinate system (GCS). The decomposition matrix was computed for two adjacent segments, and then the distal segment matrix was multiplied by the transpose of the proximal segment matrix to obtain a joint matrix. Finally, the Cardan angles were then computed to find the joint angles [58]. Lower extremity joint angles calculated included pelvis, right and left hip, right and left knee, and right and left ankle. Upper extremity joint angles calculated included thorax, right and left shoulder, and right and left elbow. The separation angle between the thorax and pelvis was also calculated. All joint angles calculated were XYZ Cardan sequences, except for the shoulder which was ZYZ, as recommended by ISB standards [59].

Joint and segment angular velocities were calculated by differentiating the rotation matrix calculated for joint angles. Once an angular velocity vector was calculated, additional differentiation provided angular accelerations. Angular velocity and acceleration were calculated for the pelvis, right and left hip, right and left ankle, thorax, right and left shoulder, and right and left elbow.

3.3.2.2.2 Kinetic Metrics

Net joint reaction forces and internal moments were calculated using inverse dynamics. Inverse dynamics in Visual3D compute net moments generated by muscles

crossing a joint assuming they are the primary controllers of the movement, and does not allow for individual muscle contributions to be determined [60]. The segment kinematics and inertial properties allow inverse dynamics calculations. The assumptions of inverse dynamics in Visual3D include equal and opposite forces and moments about a joint, and the distal end of one segment is not assumed to be located at the same point as the proximal end of the adjacent segment [61]. Net joint forces calculated included bilateral knee, shoulder, and elbow. Net internal moments calculated included pelvis, thorax, and bilateral knees, shoulders, and elbows. Joint rate of loading was calculated for the pelvis, thorax, and bilateral shoulders, and elbows using the first derivative of the calculated net internal moments.

3.3.2.2.3 Timing Events

With kinematics and kinetics calculated, key events and timing of the pitching motion were calculated. This allowed the kinematics and kinetics to be extracted at key points in the pitching motion when peaks often occur. Leg lift (LL) was defined as the global max of the proximal end position of the lead leg shank segment in the Z direction. FC was defined as the threshold cross of zero of the lead leg ankle velocity in the X direction after the global minimum velocity in the same direction. Ball release (BR) was defined as the frame when the distal end of the forearm segment crossed over the proximal end in the anterior direction after the global minimum of the center of gravity of the forearm segment in the Y direction occurred. Maximum MER and MIR were defined as the frames when global maximum and minimum of the throwing shoulder joint angle in the Z direction, respectively.

Once the timing of all key events was defined, the metrics of interest for each key event were calculated LL metrics included knee height as a percent of subject height, pelvis rotation angle, and torso rotation angle. FC, MER, and BR metrics all included shoulder abduction, horizontal abduction, and ER, elbow flexion, pelvis rotation, torso rotation, body separation, lead hip flexion, and lead knee flexion angles. FC also included stride length, which was calculated by subtracting the left foot position from the right foot position and dividing by subject height. BR also included trunk forward and lateral flexion angles. MIR metrics included shoulder IR, lead knee flexion, trunk forward flexion, and elbow flexion angles.

Phases of the pitching motion were also defined, and key kinetics calculated within these phases. The arm cocking phase was defined as FC to MER, and maximum values within this phase were calculated for shoulder anterior, superior, and medial shear forces, shoulder abduction, horizontal adduction, and IR torques, and elbow varus torque. The arm acceleration phase was defined as MER to BR, and maximum values within this phase were calculated for elbow anterior shear force and elbow flexion torque. The arm deceleration phase was defined as BR to MIR, and maximum or minimum values within this phase were calculated for shoulder compressive, posterior shear, and inferior shear forces, elbow compressive force, and shoulder horizontal abduction and adduction torques. Finally, elbow varus torque, shoulder IR torque, and shoulder posterior shear force values for the three pitches were interpolated to game velocity. After all metrics were calculated in Visual 3D, data was exported to Excel. Once all data was exported to excel, group averages and standard deviations for all metrics were calculated.

3.4 STATISTICAL ANALYSIS

Minitab (Minitab Inc., State College, PA) was used for determining significant differences between arms and correlations. Descriptive statistics including mean and standard deviation were calculated. A distribution test and an outlier test were performed for all data. Pearson's correlation was run initially to identify correlations between clinical measures and kinetics. Linear regression was then performed and plotted for each correlation and R^2 and p-values were reported.

A NN was created in Matlab (Mathworks, Natick, MA) to investigate predictive modeling. The regression learner neural network (RLNN) application predicts data by training the model. Training the model involves machine learning; inputting known predictor and outcome data. Training allows the model to then predict the output using only inputs. 4-fold cross validation was selected to validate the model since the sample size (12) was too small for holdout validation. Cross-validation works by partitioning the data into a specified number of folds (4), training the data using out-of-fold observations, and using in-fold observations to estimate the model performance.

CHAPTER 4: RESULTS

Twelve subjects (n=12, 9 right hand D, 3 left hand D, with averages of: age: 21.0 years ± 2.4, height: 184.1 cm ± 7.5, and weight: 90.4 kg ± 14.0) completed both the clinical measures and pitching biomechanics test sessions and were included in statistical analysis. An outlier test was performed using Minitab (Minitab Inc., State College, PA), and outlier data points were excluded for linear regression analysis. An additional subject was excluded entirely for statistical analysis because of a key clinical measure being an outlier. This chapter summarizes the results from the testing sessions and statistical analyses.

4.1 CLINICAL MEASURES

Means and standard deviations of each clinical measure of interest were calculated in Minitab (Minitab Inc., State College, PA). Statistical analysis of clinical measures consisted of paired t-tests to determine significant differences between D and ND metrics. The p-value was set to 0.05. Table 4.1 displays the ROM and grip strength means, standard deviations, and p-values. The D arm had significantly more ER ROM (p-value=0.001), and total ROM (p-value=0.027) than the ND arm. No statistically significant differences were found between arms for IR ROM or GS.

Table 4.1: ROM and grip strength averages and standard deviations for D and ND arms. * denotes significance.

Metric	D	ND	P-value
ER ROM (degrees)	110.4 ± 9.2	101.08 ± 5.25	0.001*
IR ROM (degrees)	73.5 ± 11.2	76.71 ± 13.14	0.227
Total ROM (degrees)	183.8 ± 17.2	177.8 ± 16.8	0.027*
GS (kg)	50.5 ± 10.5	49.9 ± 11.0	0.589

Table 4.2, 4.3, and 4.4 show the clinical measures of isokinetic strength at 90, 180, and 270 degrees per second, respectively. These measures include both concentric and eccentric IR and ER PT normalized to body weight, concentric ER to IR PT ratio, eccentric ER to IR PT ratio, and eccentric ER to concentric IR PT ratio. No significant differences were found between arms for any of the measures at all three test velocities. Eccentric PTs were consistently higher than concentric PTs in both ER and IR at all test velocities. The mean concentric ER/IR ratio was higher than the eccentric ER/IR ratio.

Table 4.2: Averages and standard deviations of isokinetic PTs normalized to body weight and strength ratios at 90 deg/sec.

Metric	D	ND	P-Value
Concentric ER PT/BW (Nm/kg)	37.8 ± 8.6	37.5 ± 9.8	0.904
Eccentric ER PT/BW (Nm/kg)	40.8 ± 10.4	44.4 ± 9.0	0.387
Concentric IR PT/BW (Nm/kg)	56.2 ± 14.3	56.3 ± 15.8	0.982
Eccentric IR PT/BW (Nm/kg)	83.0 ± 15.1	84.0 ± 17.2	0.696
Concentric ER/IR Ratio	0.70 ± 0.16	0.68 ± 0.16	0.819
Eccentric ER/IR Ratio	0.50 ± 0.12	0.54 ± 0.10	0.551
Eccentric ER/Concentric IR Ratio	0.77 ± 0.24	0.83 ± 0.22	0.622

Table 4.3: Averages and standard deviations of isokinetic PTs normalized to body weight and strength ratios at 180 deg/sec.

Metric	D	ND	P-Value
Concentric ER PT/BW (Nm/kg)	35.8 ± 6.8	34.5 ± 9.4	0.548
Eccentric ER PT/BW (Nm/kg)	41.5 ± 10.4	43.7 ± 10.3	0.347
Concentric IR PT/BW (Nm/kg)	54.3 ± 12.8	57.3 ± 12.3	0.269
Eccentric IR PT/BW (Nm/kg)	85.0 ± 16.5	88.4 ± 16.9	0.394
Concentric ER/IR Ratio	0.69 ± 0.16	0.61 ± 0.14	0.140
Eccentric ER/IR Ratio	0.49 ± 0.10	0.50 ± 0.09	0.632
Eccentric ER/Concentric IR Ratio	0.78 ± 0.17	0.77 ± 0.11	0.795

Table 4.4: Averages and standard deviations of isokinetic PTs normalized to body weight and strength ratios at 270 deg/sec.

Metric	D	ND	P-Value
Concentric ER PT/BW (Nm/kg)	35.0 ± 8.4	31.8 ± 8.5	0.228
Eccentric ER PT/BW (Nm/kg)	36.7 ± 12.0	38.7 ± 13.2	0.316
Concentric IR PT/BW (Nm/kg)	48.5 ± 10.5	51.6 ± 14.3	0.228
Eccentric IR PT/BW (Nm/kg)	80.3 ± 16.9	81.7 ± 23.8	0.997
Concentric ER/IR Ratio	0.74 ± 0.19	0.63 ± 0.14	0.079
Eccentric ER/IR Ratio	0.46 ± 0.12	0.48 ± 0.08	0.452
Eccentric ER/Concentric IR Ratio	0.77 ± 0.21	0.76 ± 0.14	0.782

The clinical measures of isometric strength at 90, 45, and 0 degrees shoulder ER are shown in tables 4.5, 4.6, and 4.7, respectively. These measures include ER and IR PT normalized to body weight and ER to IR PT ratio. The D arm had significantly lower ER PT normalized to body weight than the ND arm at 0 degrees shoulder ER (p-value=0.04). No other statistically significant differences were found between arms for any other isometric strength measures. Mean IR PTs were higher than mean ER PTs at 90 and 45, but not 0 degrees of ER.

Table 4.5: Averages and standard deviations of isometric PT normalized to body weight and strength ratios at arm positions of 90˚ ER.

Metric	D	ND	P-Value
ER PT/BW (Nm/kg)	30.8 ± 7.6	29.9 ± 6.2	0.685
IR PT/BW (Nm/kg)	43.6 ± 11.3	43.3 ± 8.1	0.912
ER/IR Ratio	0.75 ± 0.17	0.70 ± 0.13	0.402

Table 4.6: Averages and standard deviations of isometric PT normalized to body weight and strength ratios at arm positions of 45° ER.

Metric	D	ND	P-Value
ER PT/BW (Nm/kg)	37.2 ± 8.0	39.0 ± 8.1	0.276
IR PT/BW (Nm/kg)	44.5 ± 10.0	44.9 ± 12.5	0.817
ER/IR Ratio	0.84 ± 0.10	0.87 ± 0.15	0.438

Table 4.7: Averages and standard deviations of isometric PT normalized to body weight and strength ratios at arm positions of 0° ER. * denotes significance.

Metric	D	ND	P-Value
ER PT/BW (Nm/kg)	36.6 ± 9.7	39.7 ± 7.2	0.044*
IR PT/BW (Nm/kg)	33.8 ± 8.9	35.7 ± 10.4	0.353
ER/IR Ratio	1.08 ± 0.20	1.12 ± 0.28	0.557

4.2 BIOMECHANICAL MEASURES

The average pitch speed was 77.2 ± 4.2 mph. Table 4.8 shows the mean and standard deviations of the kinetics at the arm cocking and BR phases of the pitching motion. The variables were normalized to body weight and height to allow for subject-to-subject and population comparisons and to investigate correlations to the clinical measures of arm strength and flexibility.

Table 4.8: Averages and standard deviations of kinetics at the arm cocking and BR phases normalized to subject body weight and height. Torque units: Nm and Nm/kg*m, force units: N and N/kg*m.

Arm Cocking	**Metric**	**Normalized Metric**
Elbow Medial Shear Force	359.5 ± 20.8	2.18 ± 0.38
Elbow Varus Torque	123.9 ± 8.8	0.75 ± 0.14
Shoulder Anterior Shear Force	196.8 ± 51.6	1.23 ± 0.41
Shoulder Superior Shear Force	281.4 ± 60.3	1.70 ± 0.27
Shoulder Adduction Torque	73.8 ± 14.3	0.45 ± 0.08
Shoulder Horizontal Adduction Torque	30.9 ± 22.8	0.18 ± 0.13
Shoulder IR Torque	116.7 ± 26.1	0.70 ± 0.11
Ball Release		
Elbow Anterior Shear Force	697.6 ± 155.2	4.25 ± 0.96
Elbow Flexion Torque	23.6 ± 17.6	0.15 ± 0.10
Elbow Compressive Force	999.1 ± 201.6	6.03 ± 0.83
Shoulder Compressive Force	975.4 ± 188.1	5.89 ± 0.75
Shoulder Posterior Shear Force	-645.7 ± 303.9	-3.91 ± 1.82
Shoulder Inferior Shear Force	-439.4 ± 287.1	-2.75 ± 1.91
Shoulder Horizontal Abduction Torque	252.1 ± 87.2	1.55 ± 0.61
Shoulder Adduction Torque	191.5 ± 49.0	1.16 ± 0.29

4.3 CORRELATIONS BETWEEN CLINICAL MEASURES, VELOCITY, KINETICS

Correlations were investigated to identify relationships between clinical measures of arm strength and flexibility and biomechanics of the pitching motion. Normality and outlier tests were conducted for all data before correlations were investigated. All data was normally distributed. One outlier was excluded for elbow varus torque/BW*H (1.12). Correlations were investigated by first performing Pearson's correlation to identify all relationships for a variable, then linear regression on the individual correlations found. R^2, the coefficient of determination, was the primary metric used to measure correlation.

The value represents the amount of variance explained by the clinical measure. For example, 51% of the variation in shoulder posterior shear force is explained by eccentric ER/IR at 270 deg/sec. The remaining 49% may be due to other factors.

The p-level of significance was set to 0.05. Figures 4.1-4.3 show correlations found between kinetics and strength ratios. All kinetic metrics were normalized to body weight and height. The correlations found include elbow varus torque and isometric ER/IR ratio at 90 degrees ER (R^2=0.363, p=0.050, figure 4.1), shoulder posterior shear force and eccentric ER/IR ratio at 180 deg/sec (R^2=0.425, p=0.022, figure 4.2), and shoulder posterior shear force and eccentric ER/IR ratio at 270 deg/sec (R^2=0.510, p=0.009, figure 4.3), All correlations between kinetics and shoulder rotational strength ratios were negative correlations.

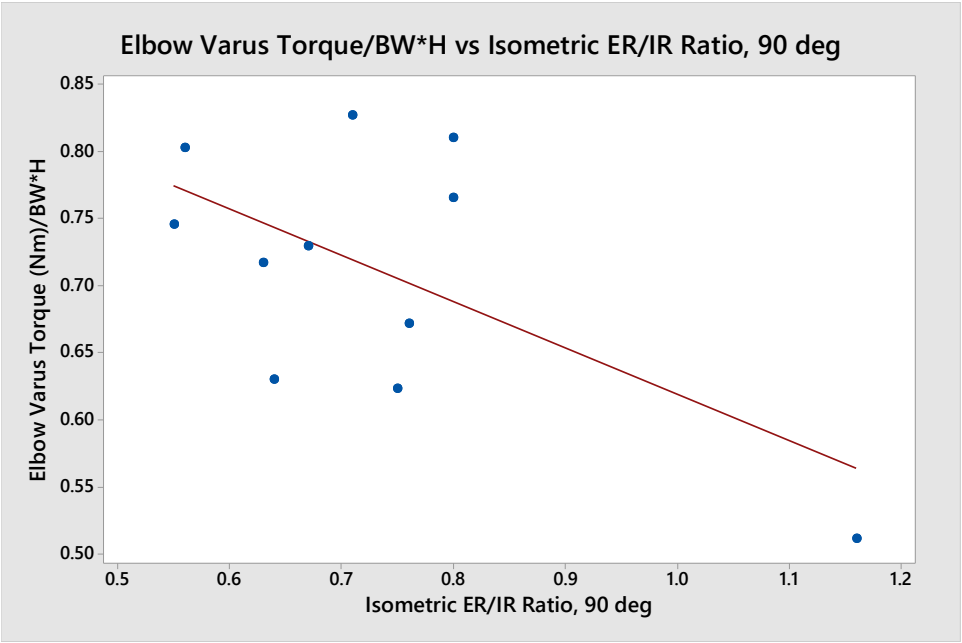

Figure 4.1: Elbow Varus torque normalized by body weight and height (Nm/(kg*m)) vs. isometric ER/IR ratio at 90 degrees of shoulder ER. R2=0.363, p = 0.050.

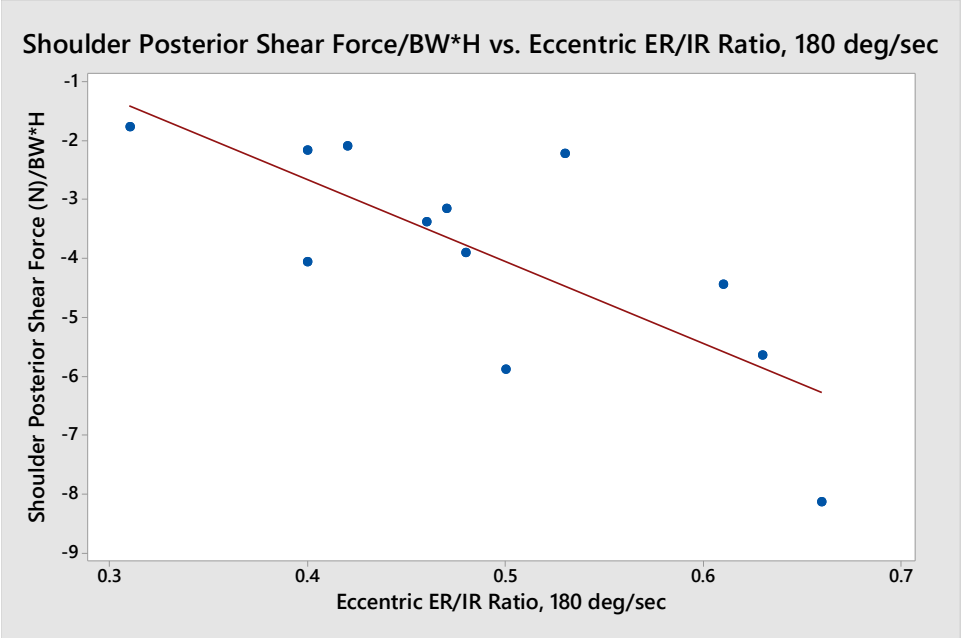

Figure 4.2: Shoulder posterior shear force normalized by body weight and height (N/(kg*m)) vs. isokinetic eccentric ER/IR ratio at 180 deg/sec. R2=0.425, p=0.022.

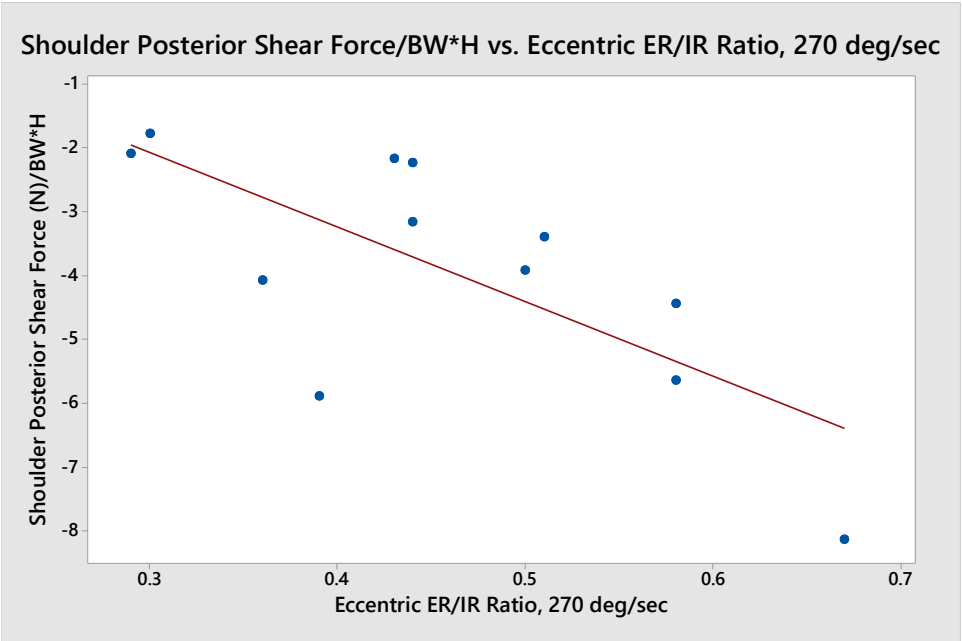

Figure 4.3: Shoulder posterior shear force normalized by body weight and height (N/kg*m)) vs. isokinetic eccentric ER/IR ratio at 270 deg/sec. R2=0.510, p=0.009.

Correlations between velocity and clinical measures of strength and flexibility were also investigated in the same manner. The p-level of significance was set to 0.05. Figures 4.4-4.9 show the correlations found between velocity and clinical measures. All correlations found were positive correlations, including velocity and grip strength (R^2=0.444, p=0.018, figure 4.4), velocity and concentric ER PT/BW at 90 deg/sec (R^2=0.357, p=0.040, figure 4.5), velocity and isometric IR PT/BW at 90 deg ER (R^2=0.350, p=0.043, figure 4.6), velocity and ER PT/BW at 45 deg ER (R^2=0.529, p=0.007, figure 4.7), velocity and IR PT/BW at 45 deg ER (R^2=0.395, p=0.029, figure 4.8), and velocity and ER PT/BW at 0 deg ER (R^2=0.702, p=0.001, figure 4.9).

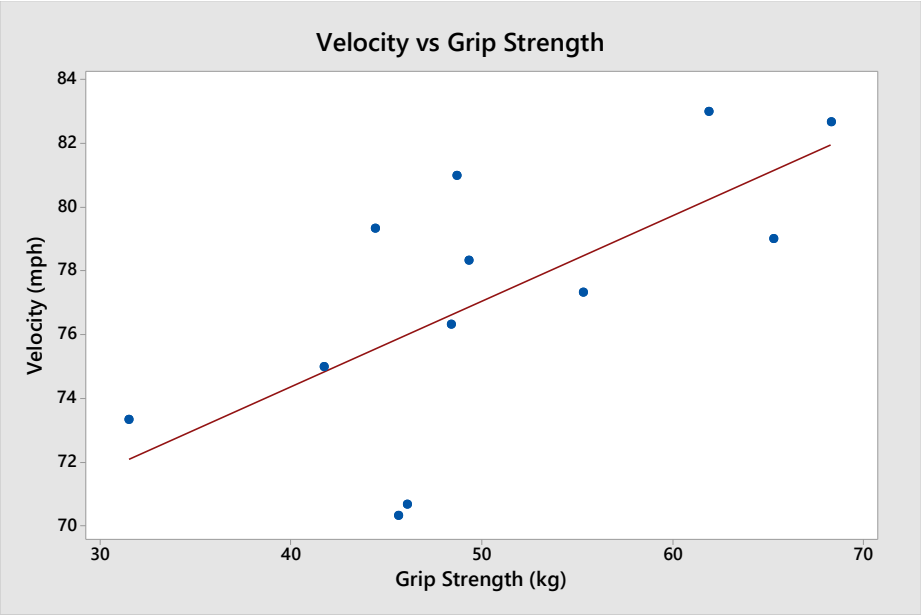

Figure 4.4: Velocity (mph) vs. grip strength (kg). R2=0.444, p=0.018.

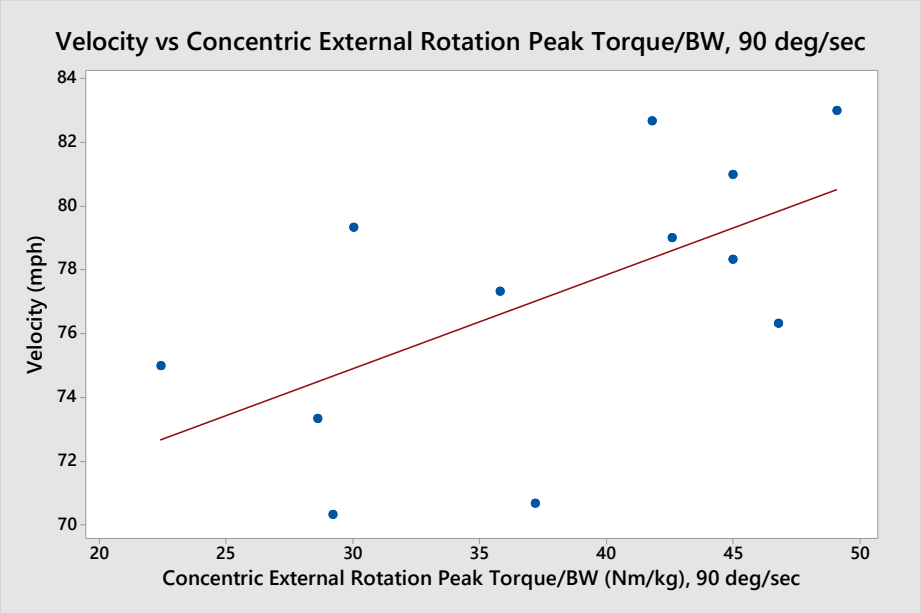

Figure 4.5: Velocity (mph) vs. concentric ER torque normalized to body weight (Nm/kg) at 90 degrees/sec. R2=0.357, p=0.040.

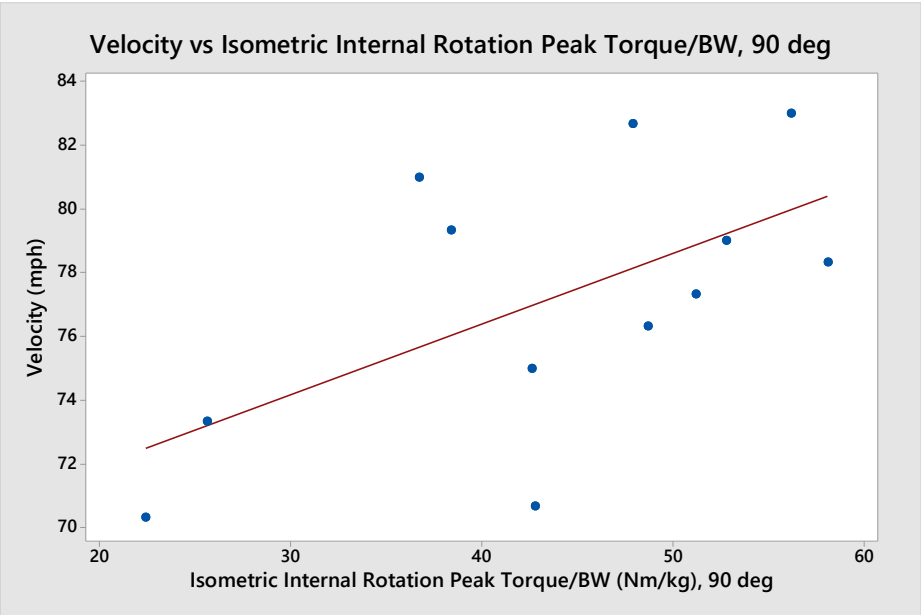

Figure 4.6: Velocity (mph) vs. Isometric IR PT normalized to body weight (Nm/kg) at an arm position of 90 degrees ER. R2=0.350, p=0.043.

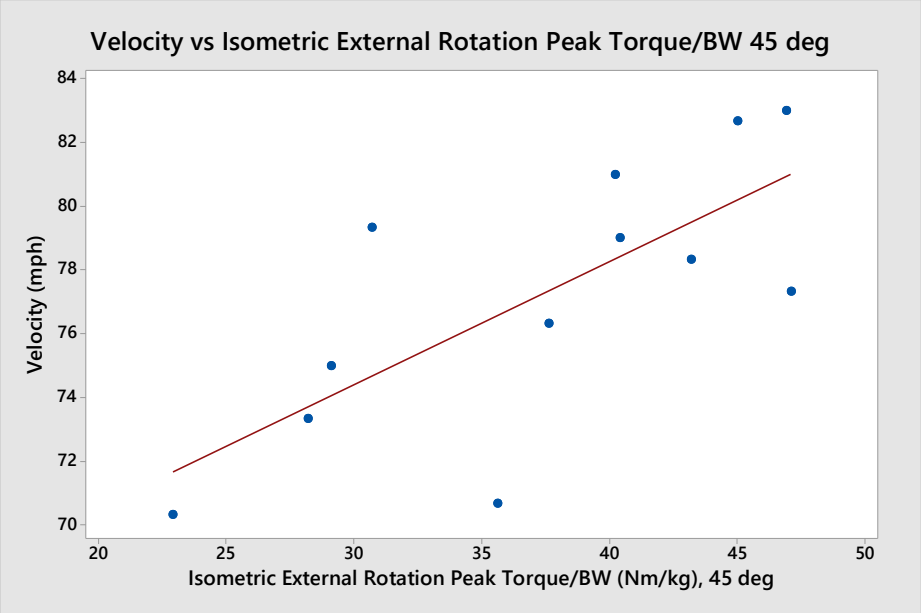

Figure 4.7: Velocity (mph) vs. isometric ER PT normalized to body weight (Nm/kg) at an arm position of 45 degrees ER. R2=0.529, p=0.007.

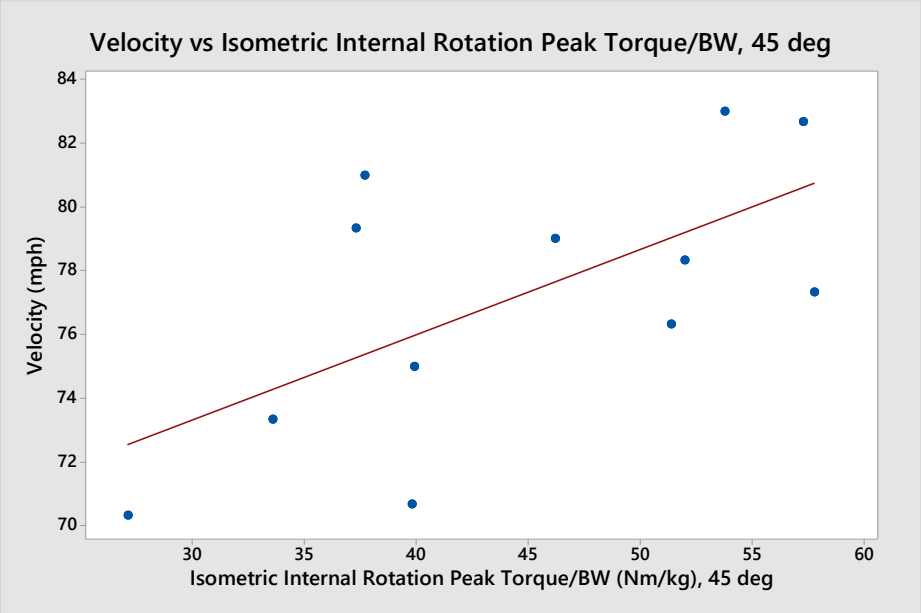

Figure 4.8: Velocity (mph) vs. isometric IR PT normalized to body weight (Nm/kg) at an arm position of 45 degrees ER. R2=0.395, p=0.029.

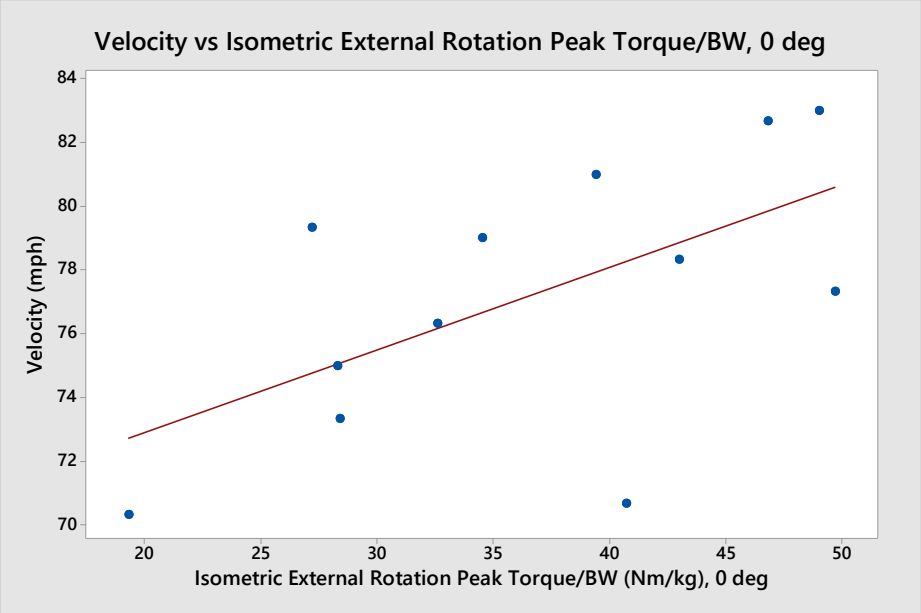

Figure 4.9: Velocity (mph) vs. isometric ER PT normalized to body weight (Nm/kg) at an arm position of 0 degrees ER. R2=0.702, p=0.001.

4.4 NEURAL NETWORK REGRESSION LEARNER

RLNNs were created to predicts fastball velocity and elbow varus torque using clinical strength measures. The fastball RLNN was trained using clinical strength measures as input with known fastball pitch speeds as outcome data. The input features selected included height, grip strength, concentric ER PT/BW at 90 degrees/sec, and isometric ER PT/BW at 45 degrees ER. These features were selected because they were all correlated with pitch velocity using linear regression, and their combination resulted in the best model performance. The primary statistic used to assess model performance is root mean square error (RMSE, standard deviation of the error). Other performance statistics include R^2 (coefficient of determination, 1=perfect fit), mean square error (MSE, square of root mean square error), and mean absolute error (MAE, similar to RMSE but less sensitive to outliers). The RLNN was able to predict fastball velocity

within 2.29 mph (RMSE=2.2924, R^2=0.70, MSE=5.2549, MAE=1.9064). The cubic support machine vector model was selected because it had the lowest RMSE. Figure 4.10 shows the response plot and figure 4.11 shows the predicted vs. actual fastball velocity.

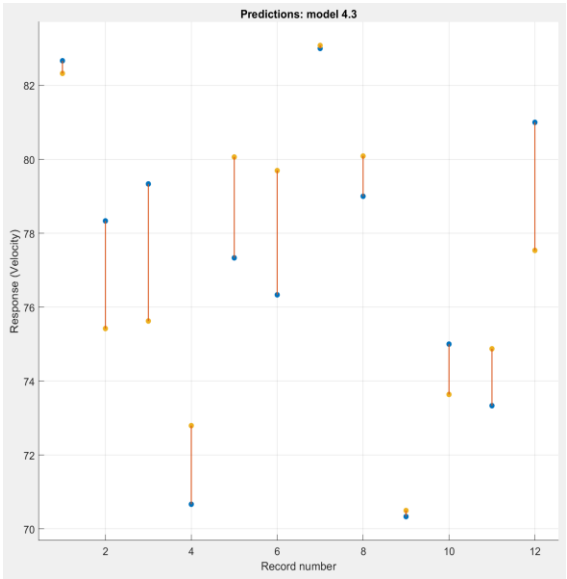

Figure 4.10: Velocity predicting cubic SVM RLNN model response plot: blue=actual, orange=predicted, red line=errors.

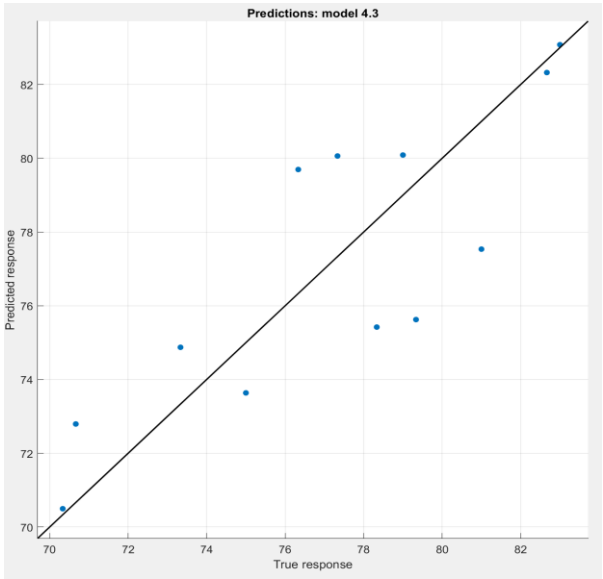

Figure 4.11: Cubic SVM NN linear regression learner model predicted vs. true fastball velocity: blue=observation, black line=perfect prediction. Model performance: RMSE=2.2924, R2=0.70, MSE=5.2549, MAE=1.9064.

The elbow varus torque RLNN was able to predict torque within 16.34 Nm on average (RMSE=16.34, R^2=0.70, MSE=266.98, MAE=12.417). A rational quadratic gaussian process regression model was used because it had the lowest RMSE value. Figures 4.12 and 4.13 show the actual vs predicted value with error, and the predicted vs true response plots, respectively.

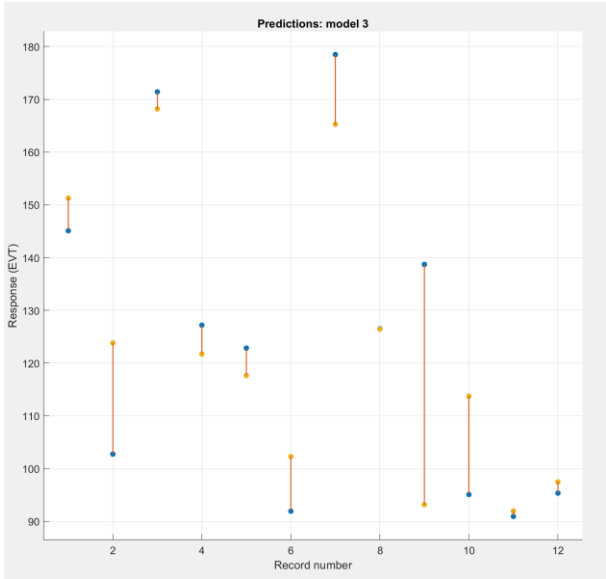

Figure 4.12: Elbow varus torque predicting rational quadratic gaussian process regression RLNN model response plot: blue=actual, orange=predicted, red line=errors.

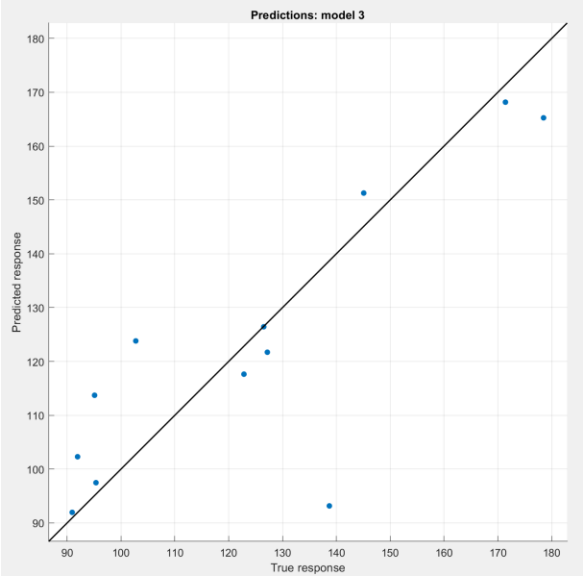

Figure 4.13: rational quadratic gaussian process regression RLNN model predicted vs. true elbow varus torque: blue=observation, black line=perfect prediction. Model performance: RMSE=16.34, R2=0.70, MSE=266.98, MAE=12.417.

CHAPTER 5: DISCUSSION

Limited research has investigated correlations between clinical measures of strength and flexibility and pitching biomechanics or using correlations to train NNs and predict key pitching metrics using clinical data. The purpose of this study was to determine correlations that exist between shoulder rotational strength, ROM, grip strength, and biomechanical metrics of the pitching motion, and to train a NN to predict biomechanical metrics using clinical data.

It was hypothesized that significant differences would be found between the D and ND arm ER and IR ROM, ER/IR strength ratios, grip strength, that negative correlations would be found between rotational strength ratios and kinetics, and that NNs can be used to predict key biomechanics using clinical data. The results of this study, outcomes of the hypotheses, and comparison to previous relevant literature will be discussed in this chapter. The practical relevance of the results, limitations of the study, and recommendations for future studies will be discussed.

5.1 CLINICAL MEASURES

5.1.1 Range of motion

Pitching puts unique demands on the shoulder that can alter the rotational ROM in the D arm. These alterations may be due to osseous changes, soft tissue changes, or a combination of both. ROM alterations are important to monitor because they may cause injury [4,41]. It was hypothesized that significant differences would be found between D and ND arm IR and ER. The hypothesis was found to be partially true. Significant

differences were found between D and ND arms for ER ROM (110.4 ± 9.2˚ D vs 101.08 ± 5.25˚ ND) and total rotational ROM (183.8 ± 17.2˚ D vs 177.8 ± 16.8˚ ND). No significant differences were found between D and ND arms for IR ROM (73.5 ± 11.2˚ D vs 76.7 ± 13.1˚ ND).

The ER ROM results of the current study are consistent with previous studies that also found ER ROM of the D arm significantly higher than the ND arm [1–4,41]. The IR ROM results contradict previous studies that found the IR ROM of the D arm significantly lower than that of the ND arm [1–4,41]. The total ROM results also contradict previous studies that found the D arm to have less total shoulder rotational ROM [2,4,41], or did not find any significant difference [3]. The significant difference in total ROM in our study is likely due to the D arm having increased ER ROM without concurrent decreases in IR ROM compared to the ND arm. Figure 5.1 displays the current and previous studies ROM results. The variance in ROM values across studies was likely due to differences in methodology of testing.

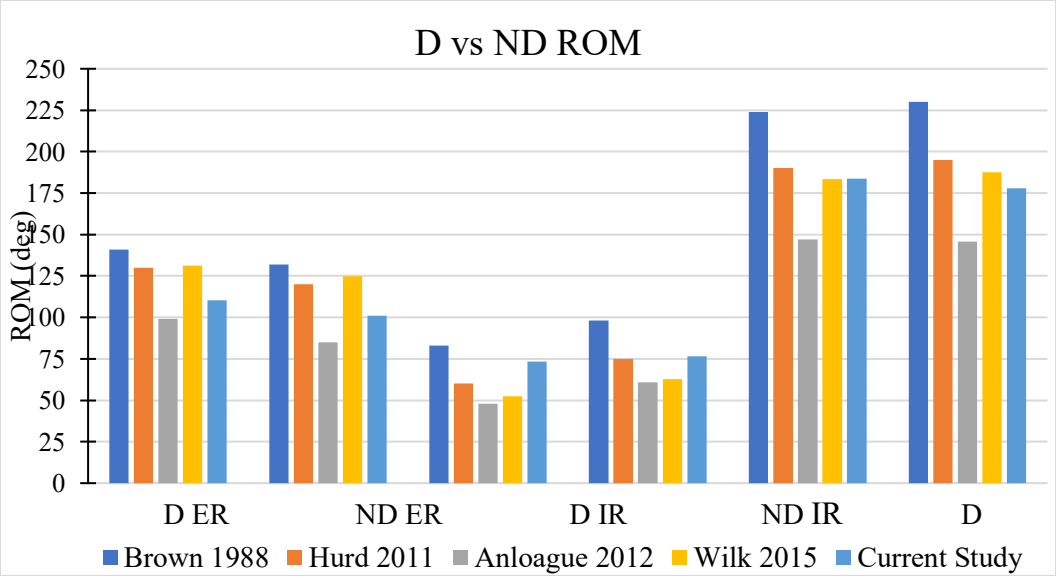

Figure 5.1: ROM results compared across studies.

The method of stabilization during shoulder ROM testing has been shown to yield significantly different results [38]. Brown et al. did not report their stabilization method [1], Hurd et al. used the humeral head stabilization method [2], and Wilk et al and Anloague et al. both used the scapular stabilization method [3,4]. Our study used the scapular stabilization method. Scapular stabilization may be the best method for measuring glenohumeral rotational ROM because it does not interfere with the arthrokinematics of the glenohumeral joint, and eliminates scapular motion [38]. In addition to stabilization, the plane of the humerus may have differed depending on the study, with three studies testing in the scapular plane [2–4] and another study not specifying plane [1]. Our study measured ROM in the scapular plane. The scapular plane is preferred because this is the functional plane of the glenohumeral joint and does not put any soft tissue in tension before measurement [38]. The end ROM in this study was defined as when scapular motion occurred or if subjects indicated they felt they had reached the end of their ROM or had any discomfort or pain. It is possible that pitchers were more apprehensive during IR testing of the ND arm since it does not undergo full rotational ROM as often as the D arm.

Another difference between studies that may account for differences in ROM was population. The current study tested collegiate pitchers (n=12) along with another study (n=42 [3]), while two studies tested professional pitchers (n=41) [1], n=296 [4]), and one tested high school pitchers (n=210 [2]). It has been shown that total ROM decreases with age in youth baseball players [62], however that trend was not seen with these studies. ROM decreases with age may be complete by high school, or the differences in sample size and stabilization method prevented this trend from being realized across the studies.

The repetitive, high stress motion of pitching has been shown to create adaptations to D arm rotational flexibility [1–4,41]. Whether these changes are due to alterations to osseous bone tissue, soft tissue, or both has yet to be fully determined. Studies have shown the existence of increased D arm humeral retroversion in pitchers that also had significant differences in both IR and ER ROM [63,64]. The different positioning of the humerus in the transverse plane could be the primary cause of ROM differences between arms. Humeral retroversion is highest in adolescence, and the humerus naturally derotates with age. With most of the derotation occurring by the age of 8, and full adult values of retroversion occurring between 16-19 [65]. It is possible that pitching at a young age prevents derotation and results in increased D arm retroversion, which then alters glenohumeral ROM. A study by Meister et al. showed decreased total shoulder rotational ROM among youth baseball players with increased age, with the most dramatic change occurring between the ages of 13 and 14 [62]. These osseous changes affecting the derotation of humeral retroversion may be primarily responsible for ROM alterations in youth baseball players, with future alterations due to soft tissue effects.

However, there is also evidence that soft tissue adaptations contribute to the ROM differences. A significant decrease in both D arm IR and total ROM has been shown immediately after and 24 hours after pitching [39]. This suggests musculotendinous adaptations are also responsible for changes in shoulder rotational ROM. Specifically, muscular and posterior capsule tightness have both been suggested to cause decreases in IR ROM [66]. Agonist to antagonist strength ratios may also alter ROM; and significant differences of ER/IR strength ratios between arms of pitchers have been found [6,7].

It is not apparent what precise glenohumeral rotational ROM is ideal to avoid injury, however in general decreased ROM may increase injury risk. Studies have investigated injury risk of pitchers as it relates to glenohumeral rotational ROM with varying results [4,41,67]. Conclusions range from decreased D ER ROM correlated to injury and surgery [4], to pitchers with GIRD twice as likely of injury (but not statistically significant) [41], to no statistically significant correlations of any shoulder ROM measure and injury [67]. The musculotendinous factors that may also contribute to ROM alterations may be primarily due to the eccentric loads placed on the ER muscles. However, these alterations may be managed by stretching, shoulder exercises, and icing, especially following pitching [39].

5.1.2 Grip strength

Grip strength may be correlated with pitch velocity [49,68] and higher levels of professional baseball players have displayed significantly higher grip strength [69]. It was hypothesized that the grip strength of the D hand would be higher than the ND. This hypothesis was not supported, as no significant differences were found between D and ND arms for grip strength (50.5 ± 10.5 kg D vs 49.9 ± 11.0 kg ND). These results contradict previous studies that showed D grip strength significantly higher than ND in pitchers [44,45], as well as non-baseball players [45]. Tajika et al. tested high school pitchers (n=133) using a Takei Scientific Instruments dynamometer, and recorded the average of three trials [44], while Jarit et al. tested collegiate baseball players as well as a control group of non-baseball players (n=88) using a Jamar dynamometer, and recorded the highest of three trials [45]. The position of testing grip strength was the same for all

studies with the arm adducted at the side, 90˚ elbow flexion, and forearm and wrist in the neutral position. Due to similarities to the study by Jarit et al, it was unexpected that our results did not align with theirs, although this study averaged the trials, while Jarit et al. took the maximum trial.

Flexor muscles are the primary contributor to grip strength and attach to the medial epicondyle to help provide elbow stability. The pronator teres, flexor carpi radialis, palmaris longus, and flexor digitorum superficialis all provide dynamic support to valgus stresses placed on the elbow and the UCL [21]. It is possible that increased grip strength provides more muscular stability to the elbow joint and decrease the amount of torque absorbed by ligaments. A decrease in grip strength may contraindicate throwing, as more torque would be absorbed by the ligaments, although only one study to our knowledge has investigated the relationship between grip strength and injury, and found no statistically significant relationships [48]. More research must be conducted to establish normal D and ND grip strengths as well as the relationships between D grip strength and velocity and injury.

5.1.3 Isokinetic Strength

Monitoring the balance between the IR and ER strength is important for shoulder health. Shoulder injuries are the most common for pitchers [19], especially the posterior shoulder muscles, which are often overloaded from the repeated eccentric activity during deceleration. IR muscles may be selectively strengthened, while ER muscles are eccentrically overloaded [19]. ER/IR ratios are a useful way to measure the balance between the rotator muscles. It was hypothesized that significant differences would be

found between arms for both concentric and eccentric ER/IR isokinetic strength ratios. The results contradicted this hypothesis, as no significant differences were found between arms for concentric ER/IR strength ratios at any of the three test velocities (90, 180, or 270˚/sec) (figure 5.2). Additionally, no significant differences were found between arms for eccentric ER/IR strength ratios, or the functional eccentric ER/concentric IR strength ratio at any test velocities.

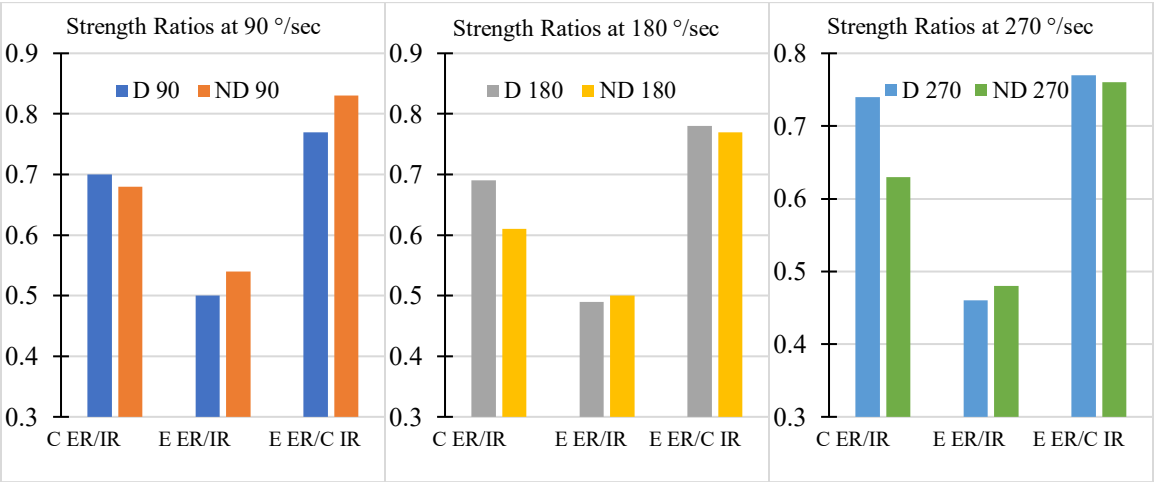

Figure 5.2: D and ND shoulder rotational strength ratios at 90, 280, and 270˚/sec.

The concentric results are in partial agreement with previous literature. Some studies have found no significant differences between arms for concentric ER/IR strength ratios at test velocities ranging from 90 to 300˚/sec [6,8–11], although most showed a trend of lower D arm ratios [6,8,9,11]. Two additional also displayed this trend [5,12], but did perform statistical analysis to determine differences. Two studies have found significant differences, with the D arm displaying lower ratios than the ND arm at 90˚/sec [6,7] and 240˚sec [7]. The eccentric results are consistent with the previous literature. No significant differences were found between arms for eccentric ER/IR strength ratios at

test velocities ranging from 60 to 300˚/sec [6,10,11]. Although not significant, in this study and previous, the D arm had a trend of lower mean ratios at all test velocities. The only other study that calculated the functional eccentric ER/concentric IR strength ratio did not run statistical analysis, but found the D arm lower than the ND at 300˚/sec. In this study, the D arm functional ratio was lower than the ND at 90˚/sec, but higher at 180 and 270˚/sec.

Directly comparing our results to previous literature was limited due to differences in subject skill level and testing velocities. Some studies tested high school pitchers [6,7], while others included collegiate [9,11,12], and professional [5,8,10]. More advanced skill levels with increased access to strength and conditioning experts, equipment, and detailed programs may result in more balanced rotational strength ratios. Varying test velocities also yields different results. For concentric contractions, most studies show a trend of decreased peak torque with increased rotational velocity [5,7–11]. Eccentric contractions showed a trend of increased peak torque with increased rotational velocity [6,10,11]. This agrees with the force-velocity physiological relationship of muscle tissue. This study saw these trends for the D arm during concentric PT/BW, while eccentric PT/BW showed increases from 90 to 180 ˚/sec but decreased from 180 to 270˚/sec for both IR and ER. It is possible that the subjects were apprehensive to give maximum effort eccentric contractions at this test velocity. However it would seem that higher rotational velocities are more relevant to baseball considering the rotational velocity the shoulder undergoes during pitching (up to 7000˚/sec) [17].

For pitchers in general, the trend of lower D arm ratios compared to the ND arm is due to lower ER strength and higher IR strength in the D arm vs the ND arm.

Differences in concentric IR between arms are expected since the muscles responsible for IR contract concentrically during pitching. Thus, the act of pitching inherently strengthens these muscles via plyometrics as they are stretched at MER, before contracting concentrically to accelerate the arm [43]. Contrary to the IR muscles, the ER muscles contract eccentrically during pitching to decelerate the arm after BR. The ER muscles do not undergo plyometric strengthening during pitching as the IR muscles do, rather they must resist stretching eccentrically [43]. While the IR are naturally strengthened during pitching, the ER muscles can instead overload, leading to microtraumas and injury [19]. The ER muscles should be monitored closely and targeted during offseason training to prepare for the high demands of pitching. It may be beneficial to incorporate eccentric training, as it has been shown more effective in increasing muscle hypertrophy and strength than concentric training [70], and it is the primary contraction that ER muscles will undergo during pitching. Pitchers should have the goal of creating a higher eccentric ER/IR ratio in the D arm, using the ND arm as a baseline during offseason training.

5.1.4 Isometric Strength

Like isokinetic strength ratios, isometric ER/IR ratios are a valuable way to quantify the balance between the rotator muscles. Isometric glenohumeral rotational strength was in three different positions of ER. The hypothesis that significant differences would be found between arms for both concentric and eccentric ER/IR isometric strength ratios was found to be false. No significant differences were found between ER/IR ratios in any position of ER. The ER/IR ratios increased as the ER position decreased in both

arms. The muscle's force production capability combined with the passive tension are highest when the muscle is maximally stretched. Therefore, ER strength should be highest in a position of 0˚ ER, and IR strength should be highest in a position of 90˚ ER. Interestingly, this was not the case. For the D arm, both ER PT/BW and IR PT/BW maximums occurred at 45˚ ER. For the ND arm, the ER PT/BW maximum occurred at 0˚ ER, while the IR PT/BW maximum occurred at 45˚ ER. It is possible that since baseball players typically display increased ER ROM, there is not as much tension at 90˚ ER. The muscles may contribute more to the force production capability of the pitching shoulder than the passive tension of ligamentous restraints.

These results are in partial agreement with previous studies. Donatelli et al. measured isometric strength at 0˚ ER found the D arm ER strength significantly lower than the ND arm [14], similar with the results of this study at that position. They also found D arm IR strength significantly higher than the ND arm, which contradicts the results in this study [14]. Also contradicting our study were results from Hurd et al. that found significant differences between arms in both ER and IR strength at 45˚ ER [42].

The position of the arm, especially in ER will have a large effect on isometric strength results. This is the only study to our knowledge that tested isometric shoulder rotational strength in multiple positions of ER. The significant difference between D and ND ER PT/BW was only found at the position of 0˚ ER. Shoulder posterior shear force and horizontal abduction torque peak when the shoulder reaches 0˚ ER after BR [16]. The extremes of force and torque placed on the shoulder at 0˚ ER might explain why the D arm may be significantly weaker than the ND arm at this position, but not others. With

limited studies performed involving isometric rotation shoulder strength in pitchers, more research testing isometric strength at various positions of ER need to be conducted.

5.3 BIOMECHANICAL MEASURES

The pitching biomechanics in this study used to investigate correlations included kinetic metrics during arm cocking and arm deceleration. Several elbow and shoulder metrics peak during these phases in the pitching motion. Kinetics were chosen because of their potential to alter health and performance. Shoulder IR torque may be transmitted through the humerus to the elbow as varus torque, which is largely absorbed by the UCL [15,16]. Shoulder compressive force and horizontal adduction torque may be the primary cause of rotator cuff tears during deceleration [16]. Elbow flexion torque, and shoulder and elbow compressive forces have been correlated to increased pitch velocity [27,30,35].

Three key kinetics that are included in most studies due to implications on injury risk are elbow varus torque, shoulder IR torque, and shoulder compressive force. Our results showed that the elbow varus torque (123.9 ± 8.8 Nm) (figure 5.3), and shoulder IR torque (116.7 ± 26.1 Nm) (figure 5.4) were higher than other studies [15,16,25,26,28,32,33], while the shoulder compressive force (975.4 ± 188.1 Nm) (figure 5.5) was in the middle compared to other studies.

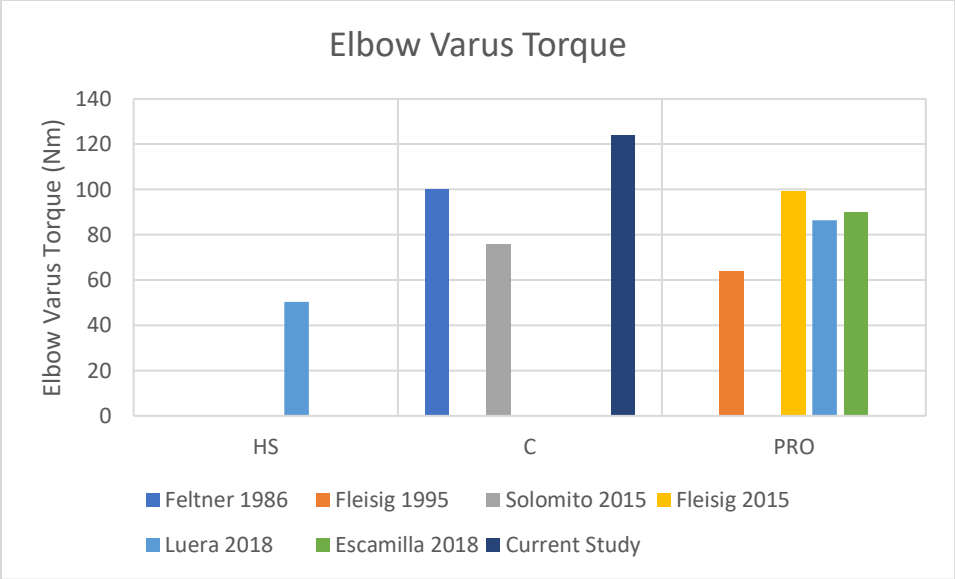

Figure 5.3: Comparison of elbow varus torque (Nm) across various levels.

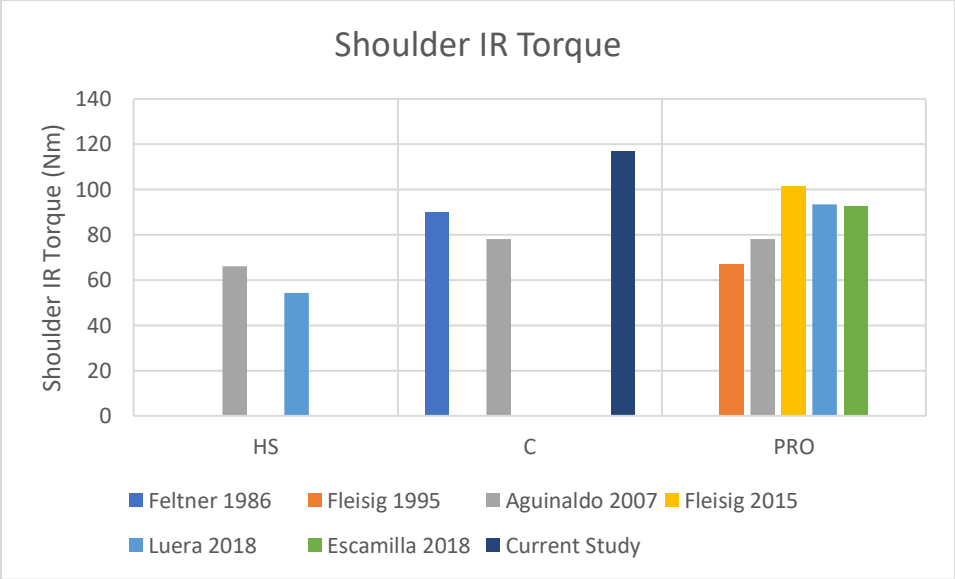

Figure 5.4: Comparison of shoulder IR torque across various levels.

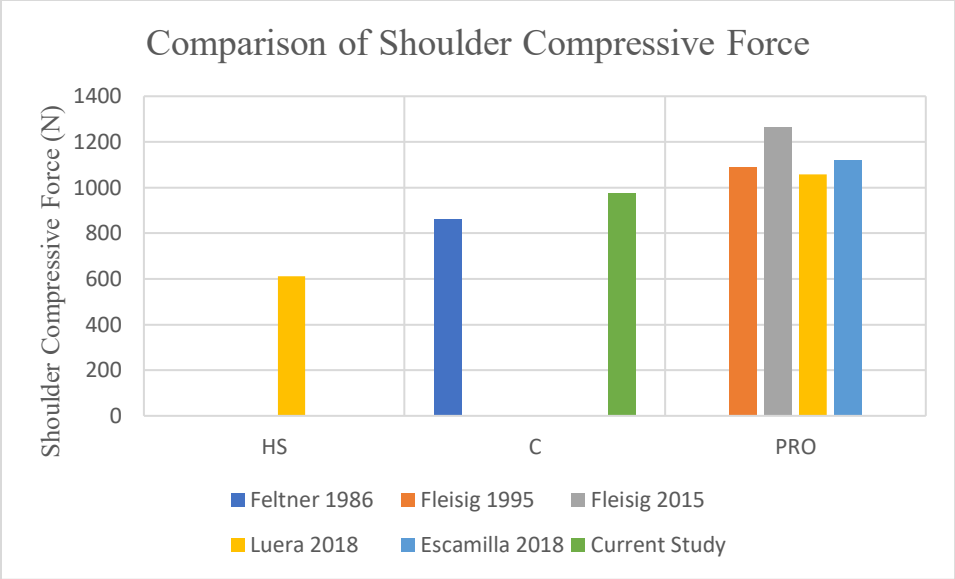

Figure 5.5: Comparison of shoulder compressive force across various levels.

In general, all three key kinetics appear to increase with level of competition, although elbow varus torque to a lesser extent. This is expected as mass and height typically increase with level of competition. Normalizing kinetics by mass and height as this study did may be more useful for comparing across populations, ages, and skill levels. Aguinaldo et al. found professional pitchers had significantly lower normalized elbow varus torque compared to high school pitchers, and significantly lower normalized shoulder IR torque compared to college, high school, and youth pitchers [28].

Differences in methodology including marker sets, marker placement, sampling rate, and biomechanical models may contribute to differences in pitching kinetics. Studies have used different marker sets, ranging from 14 to 46 total markers [16,25,26,28–30,32,33]. Differences in marker placements and joint center calculations cause significant differences in results [71,72]. Marker placement is important because it defines the segment ends and joint centers. Both kinematics and kinetics are affected by different segment and joint center definitions. Sampling rates also varied greatly, from

120 up to 480 Hz [15,16,25,26,28–30,32,33]. In general, sampling rate should be at least twice the maximum frequency of the movement to avoid aliasing [73].

Differences in biomechanical models also lead to kinematic and kinetic differences [74]. With different marker sets and locations used, segments and joint centers are defined differently. This will change how the biomechanical model is defined and how kinematics are calculated. Differences in kinematics will also be reflected in kinetics since they are calculated via inverse dynamics. Segment mass and geometry differences also affect kinetic calculations. Details on biomechanical models and calculations are sparse in literature. Overall, differences in data collection methodology may have a bigger impact on pitching analyses due to the highly dynamic nature of the motion, which may account for large differences in kinetics.

5.4 CORRELATIONS

5.4.1 Clinical measures and kinetics

Investigating correlations between clinical measures and pitching biomechanics provides important insight to medical and coaching staff. Different modalities of testing can be associated to more readily identify injury risk. Discovering correlations may also allow improved strength and flexibility training strategies to decrease high kinetics. The hypothesis of negative correlations existing between rotational strength ratios and pitching metrics was found to be true. Three inverse correlations between kinetics and strength ratios were found: elbow varus torque and isometric ER/IR ratio at 90˚ ER, and shoulder posterior shear force and eccentric ER/IR ratios at both 180˚/sec and 270˚/sec. These correlations indicate that higher strength ratios may decrease the certain kinetics,

providing valuable information. It links two modalities of testing to increase the ways to evaluate injury risk in pitchers. If motion analysis is not available or practical, shoulder rotational strength testing can be performed. With known correlations, assumptions can be made about what kinetics might be of concern without performing motion analysis and calculating them. Based on these results, if eccentric ER/IR ratios are tested at 180 and 270˚/sec and are low, the pitcher may be at risk for high posterior shear force during pitching and the potential injuries associated. It is also valuable as a practical training solution to decrease high kinetics when they are found via motion analysis.

Elbow varus torque is arguably the most important kinetic metric to monitor and limit in pitchers due to its relation to UCL tears and the associated time missed [16,22,23]. The inverse correlation between elbow varus torque and isometric ER/IR ratio at 90˚ ER suggests that increasing this ratio could decrease the torque and risk of UCL injury. However, this correlation was the weakest in this study, with the lowest R^2 value and p-value equal to the cutoff for significance (0.05).

Shoulder posterior shear force may be a primary contributor to glenoid labrum injuries in combination with compressive forces [19]. The inverse correlations between posterior shear force and eccentric ER/IR ratios at both 180˚/sec and 270˚/sec suggest that rotational strength plays an important role in protecting the labrum during arm deceleration. Increasing these strength ratios, specifically eccentric ER strength, may help decrease high posterior shear forces. The presence of correlations at two of the test velocities and both eccentric ratios is encouraging to the validity of the results. The eccentric nature of the strength ratios correlated also match the action of the shoulder

posterior shear force during pitching, as muscles contract to resist anterior translation of the humerus [16].

Only one previous study has investigated correlations between shoulder rotational strength flexibility and pitching kinetics [13]. Hurd et al. used a handheld dynamometer to test isometric rotational strength of high school pitchers and calculated kinetic metrics from motion analysis using a four-segment upper extremity model. They found negative correlations between ER ROM and elbow adduction (varus) and shoulder IR torque [13], suggesting that increasing ER ROM may be effective for decreasing high elbow adduction or shoulder IR torques. However, this may only be a feasible recommendation for pitchers that don't already display the high levels of ER ROM in the D arm. They also found a positive correlation between shoulder ER torque and IR strength [13], which may have limited meaning as shoulder ER torque has not be associated with injury.

Figure 5.6 compares the R^2 values for the correlations found in this study and by Hurd et al. R^2 represents the amount of variance of the kinetic metric explained by the clinical metric. It is always between 0 and 1, and higher values indicate a better correlation. All R^2 values for correlations found in this study were higher than those from Hurd et al. While the correlations between strength metrics and pitching kinetics found are encouraging, more research needs to be done to verify these correlations across various populations of pitchers before applying them in practice.

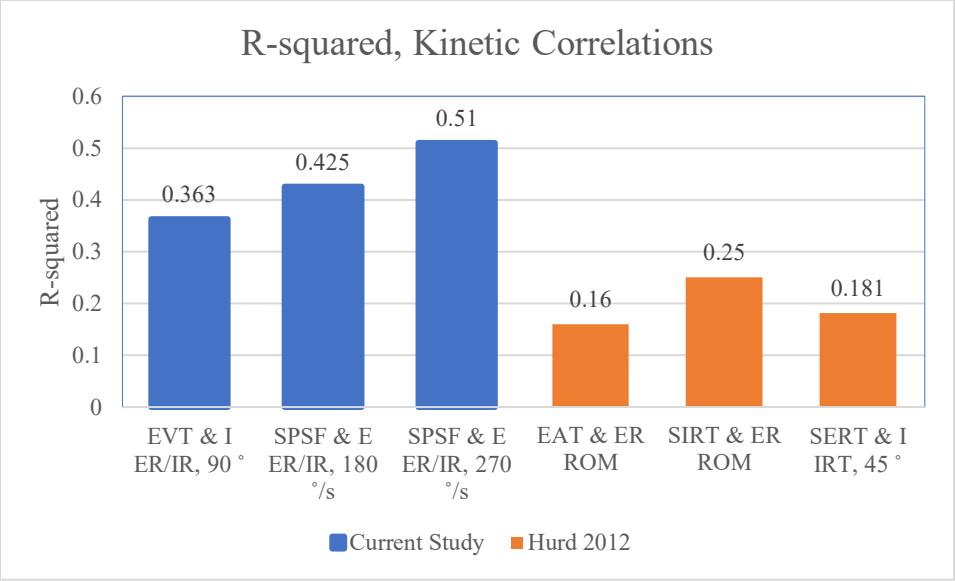

Figure 5.6: R-squared values for correlations found in this study and Hurd et al. [13]. (EVT = elbow varus torque, Ism = isometric, SPSF = shoulder posterior shear force, Ecc = eccentric, SAT = shoulder adduction torque, EAT = elbow adduction torque, SIRT = shoulder internal rotation torque, SERT = shoulder external rotation torque, IRT = internal rotation torque)

5.4.2 Clinical measures and velocity

Correlations were also investigated between clinical measures and velocity. This knowledge would allow for improved strength training routines with the goal of increasing velocity. The causes of decreases in velocity could be revealed as potential weakness or injuries to muscles and soft tissue that contribute responsible for rotational motion. Projected velocity gains during training or recovery could be used as targets for increased rotational strength.

Positive correlations were found between velocity and grip strength, concentric ER PT/BW at 90˚/sec, isometric IR PT/BW at 90 and 45˚ ER, isometric ER PT/BW at 45 and 0˚ ER. Of the six correlations found in this study (figure 5.7), isometric ER PT/BW at 0˚ ER was the strongest, explaining 70.2% of the variability in pitch velocity. This

correlation, along with the correlation of isometric ER PT/BW at 45˚ ER, indicate that ER strength between arm positions of 0 and 45˚ ER are key to pitch velocity. The arm is in this position between BR and MIR, when the ER muscles are decelerating the arm. Thus, the ability of the ER muscles to decelerate the arm after BR may be a limiting factor in velocity. Increasing the strength of ER muscles, especially at the relevant ER range may increase velocity.

Correlations were also found between isometric IR PT/BW at arm positions of 90 and 45˚ ER. The arm is within that range of ER just after BR as the arm begins to decelerate [17]. This position is not especially relevant to IR torque, which peaks just before MER and is low during deceleration [16]. It is possible that a stronger correlation would be found between velocity and isometric IR strength at an arm position greater than 90˚ of ER, as IR torque peaks during pitching with the arm near 180˚ ER. However, this is not practical to measure, as the arm only reaches that level of ER briefly and dynamically.

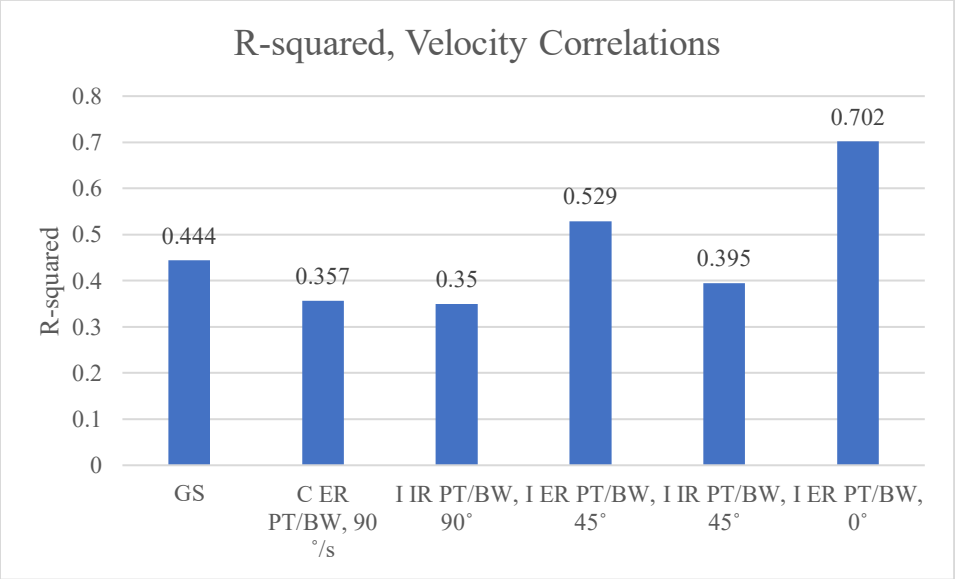

Figure 5.7: R-squared values for correlations between velocity and clinical measures.

Few studies have investigated correlations between clinical measures and pitch velocity [50,51]. Clements et al. found a correlation in adolescent players between isometric IR PT/BW and velocity [51], agreeing with the results of this study. However, Bartlett et al. found no correlations in professional pitchers between velocity and concentric IR or ER PT at 90˚/sec [50], contradicting the correlation found in this study.

The results of this study also indicated that grip strength, provided by flexor muscles primarily and extensor muscles secondarily, contributes to pitch velocity. These muscles flex the wrist and finger as the ball is released to increase spin. They may also protect the UCL by absorbing the varus torque experienced at the elbow joint. The correlation to grip strength is in partial agreement with previous literature. Pedegana et al. found a correlation between wrist extension strength and pitch velocity [49]. However, Bartlett et al. found no correlation between wrist extension or wrist flexion strength and pitch velocity [50]. These studies are slightly different, as they measured peak torques of wrist flexion and wrist extension independently on professional pitchers [49,50]. More research should be done on the kinematics of the fingers, hand, and wrist during pitching to determine the ROM experienced by each, as well as to verify the correlation found in this study.

5.5 NEURAL NETWORK

NNs can be useful to for making predictions based on known data. Correlations between clinical measures and velocity and pitching kinetics can be utilized in NNs. Creating a model that can predict velocity and pitching kinetics would be useful for multiple reasons. Kinetics linked to injury could be determined using easily measurable

strength metrics. Velocity could be determined without throwing. Predictive NN models were created using clinical measures with known correlations to pitch velocity and elbow varus torque.

The RMSE is the standard deviation of the error. The RMSE of the regression learner NN created to predict pitch velocity was 2.2924. This means that the model can predict pitch velocity within 2.29 mph on average. The average fastball velocity of all subjects was 77.19 mph; therefore, the average error of the model was 2.97%. The input features used to predict velocity included height, grip strength, concentric ER PT/BW at 90˚/sec, and isometric ER PT/BW at 45˚ ER. Although there were more metrics correlated with velocity, adding more than four metrics decreased the accuracy of the NN. An accurate velocity-predicting model is useful to players, coaches, scouts, strength and conditioning coaches, and clinicians alike. This model could be used to predict maximum velocity without maximum effort throwing. This could be useful during offseason training to monitor how strength gains are likely to affect pitch velocity. Projections of velocity gains based on growth to the predictive metrics would be useful goals to strength coaches and athletes. Improvements to young players who are still growing could be projected, providing a valuable scouting tool.

A regression learner NN was also created to predict elbow varus torque. The RMSE was 16.34. The average elbow varus torque of all subjects was 123.86, indicating the average error of the model was 13.19%. With more data to improve accuracy, this model could be used to predict elbow varus torque without performing a biomechanical analysis. This would be useful because the equipment and knowledge necessary to perform a biomechanical analysis is expensive and not always readily available.

Cross-validation was used to train the models. Larger datasets can use holdout validation for greater accuracy. A cubic support vector machine model was used to predict pitch velocity. This model was chosen because it predicted the velocity with the highest accuracy. Support vector machine regression is a supervised machine learning algorithm that finds a hyperplane that contains all the output data within a defined distance [75]. When there is more than one input, kernelling allows data to be mapped into higher dimensions, allowing the regression line to become a regression plane. Support vector machines work well with small data sets [75]. A rational quadratic gaussian process regression model was used to predict elbow varus torque. The output is modeled with a probability distribution over a space of functions for Gaussian process regression [76]. A further in-depth analysis of the types of models used in NNs is beyond the scope of this study.

NNs have allowed joint torques during squatting to be predicted based on simple inputs of barbell mass and horizontal and vertical displacement [52]. The current study is the only one to our knowledge that has investigated the use of regression learner NNs to predict pitch velocity and pitching kinetics. Future research should continue to investigate correlations between clinical strength and flexibility measures and pitching kinetics. These relationships can then be used to create more accurate predictive NNs. The kinetics linked to injury such as elbow varus torque, shoulder IR torque, and shoulder posterior shear force would be the most useful to be able to predict. Discovering correlations to other muscle groups may also prove useful. NN predictions of increased velocity and decreased torques based on strength gains could be used as offseason training goals and

scouting projections. Training NNs on larger data sets may also allow for more accurate models.

5.6 STUDY LIMITATIONS

There are several limitations that should be acknowledged for this study. The primary limitation is the small sample size. Thirteen pitchers were recruited for the study, and the data from one pitcher was excluded due to outliers. With data from only twelve pitchers to perform statistical analysis on, smaller differences may go undetected. Power analysis for the differences between D and ND arms ER, IR, and total ROM indicated that with an alpha level of 0.05 and power of 0.8, the minimum difference that could be detected for each were 6.22, 7.83, and 7.28˚, respectively. Any smaller differences would require a higher sample size to detect with the same alpha level and power. This may have contributed to some type II error where no significant differences were found in this study while previous studies did.

The effort and apprehension level of the subjects may have decreased the accuracy of clinical measures. For ROM testing, to prevent injury subjects were instructed to indicate when they felt the end of their ROM was reached, or if they felt any pain or discomfort. It is possible that subjects have differing tolerance levels or discomfort when being stretched to maximum ROM in shoulder rotation. The effort level during rotational strength testing may have also differed between subjects. Subjects were instructed to give maximum effort, but effort level cannot be fully controlled. The isokinetic strength testing may have caused fear or apprehension in some, preventing truly maximum effort. Maximum effort eccentric contractions may feel unnatural due to

their “losing” nature of isokinetic eccentric contractions. Since the dynamometer moves at a constant velocity throughout isokinetic testing, subjects cannot slow it down during the eccentric portion. While athletes do undergo eccentric contractions during strength training, it is typically in a controlling manner before a concentric contraction, not a maximum effort failure contraction. This study also did not allow for submaximal contractions before testing. This may have allowed for familiarity and increased comfort with the test for the first arm tested.

The order of measurement for the clinical testing session was not randomized. For ROM, the right arm was always measured first, followed by the left. For strength testing, the ND arm was always tested first, followed by the D arm. It is possible that subjects were less apprehensive, and more familiar with the testing protocol after the first arm was measured. For the strength testing, it is also possible that the ND arm was more warmed up during testing than the D arm. Rotational strength testing of each arm took about 15 minutes. Between arms, subjects got out of the dynamometer chair and were instructed to repeat stretches if they desired, but it was not mandatory. Future studies should randomize their order of testing arms. While the two test sessions were separated by a minimum of two days, subjects were not always prohibited from exercising or throwing before the test sessions. Explicitly requiring subjects to avoid throwing and exercising during the span of the test sessions may be more appropriate.

5.7 FUTURE STUDIES

Future studies should continue to investigate correlations to pitching kinetics. Specifically, correlations to clinical measures of strength and flexibility are useful to find

because they are easy to measure and can be improved through training. A higher subject population may allow for more significant differences and correlations to be found. Testing various skill levels of pitchers may also yield useful results. Due to differences existing between kinematic and kinetics in pitchers at different levels of skill [25,28,31], correlations may also differ.

Future studies should also continue to investigate how correlations can be used to create NNs. A regression learner NNs that can predict elbow varus torque would be useful to quantify torque without a biomechanical analysis. Characterizing this torque is important because of its link to UCL tears [16,22]. NNs could also be created for other kinetics that are linked to injury and velocity. If positive correlations are found between strength metrics and velocity, a predictive NN could be used to create training goals by projecting velocity gains from strength gains.

Measuring isometric rotational strength at different arm positions could be useful. The metric with the strongest correlation to velocity in the current study was isometric ER PT/BW at 0˚ ER. The only significant difference between rotational strength of the D and ND arm was also found at this test position. More research should be done on investigating the role of the rotator muscles at different positions of ER. Isokinetic eccentric strength should also be investigated further by future studies. Neither the current study or any previous studies [6,10,11] have found significant differences between D and ND eccentric strength. This is unexpected, since the posterior shoulder of the D arm undergoes an eccentric contraction during pitching. The eccentric ER/IR ratio does appear important, as it was correlated to shoulder posterior shear force at two test velocities in the current study. Future research should test larger subject populations for

significant differences between arms as well as correlations to kinetics and velocity to continue to determine the significance of eccentric contractions.

Measuring strength and flexibility metrics of the full body could also uncover useful correlations. The current study focused on glenohumeral joint flexibility and strength only, but many other joints and muscles are important to pitching and may yield useful correlations. Lower extremity, rotational, and back strength and flexibility are a few additional areas that future research should investigate.

5.8 SUMMARY

Minimal research has been done on correlations between clinical measures and kinetics of pitching, as well as using correlations to create predictive NNs. This study found correlations between isokinetic and isometric shoulder rotational strength, flexibility, grip strength, and pitching kinetics and velocity. A NN was also created to predict pitch velocity based on clinical measures.

CHAPTER 6: CONCLUSION

The purpose of this study was to determine correlations between shoulder rotational strength and ROM, and kinetics during pitching determined by motion analysis. Baseball pitching involves repetitive, high stresses to the D arm that may alter the soft tissue responsible for controlling the biomechanics. The central hypothesis was that correlations exist between ER/IR ratios and pitching kinetics. The rationale of this study is that new evidence on relationships between clinical measures and pitching biomechanics would associate different modalities of testing (i.e. strength, ROM, motion analysis, NNs) to identify risk of injury, which would be useful to medical and coaching staff alike. It may reveal strength and flexibility training strategies to decrease abnormally high kinetics.

Twelve collegiate baseball pitchers completed two test sessions. The clinical measures session tested shoulder rotational ROM, isokinetic and isometric strength, and grip strength. The motion analysis session tested pitching biomechanics. Paired t-tests were performed to investigate differences in strength and ROM between the D and ND arms. Linear regression was performed to determine correlations between clinical measures and kinetics and pitch velocity. A regression learner NN was created to predict pitch velocity and elbow varus torque using clinical measures as inputs.

The D arm had significantly higher ER and total ROM compared to the ND arm. No significant differences were found between arms for IR ROM. Hypothesis 1 was partially supported (significant differences will be found between limbs for IR and ER ROM). No significant differences were found between arms for isokinetic PTs normalized to BW, or ER/IR ratios. The ND arm ER PT/BW was significantly greater

than the D arm at 0˚ ER. No significant differences were found for isometric ER/IR ratios. Hypothesis 2 was rejected (significant differences will be found between D and ND ER/IR ratios). No significant difference was found between D and ND grip strength, hypothesis 3 was rejected (significant differences will be found between D and ND grip strength). Inverse correlations were found between normalized elbow varus torque and isometric ER/IR ratio at 90˚ ER and normalized shoulder posterior shear force and isokinetic eccentric ER/IR ratio at 180˚/sec and 270˚/sec. Hypothesis 4 was supported (Inverse correlations will be found between rotational strength ratios and key pitching kinetics). Positive correlations were found between velocity and grip strength, concentric ER PT/BW at 90˚/sec, isometric IR PT/BW at 90˚ ER, isometric ER PT/BW at 45˚ ER, isometric ER PT/BW at 45˚, and isometric ER PT/BW at 0˚ ER. The NN created to predict fastball velocity had RMSE of 2.29. The NN created to predict elbow varus torque had a RMSE of 16.34. Hypothesis 5 was partially supported (trained NNs can predict key biomechanical metrics using clinical data).

The results of this study benefit clinicians, coaches, and players alike. Associating different modalities of testing allows injury risk to be more easily identified. Measuring clinical strength and flexibility may be more accessible and less invasive than motion analysis. Improved strength and flexibility training strategies can be utilized to decrease high kinetics and increase maximum pitch velocity. Increasing ER/IR ratios may decrease elbow varus torque and shoulder posterior shear force during pitching. Improving grip, ER, and IR strength may increase fastball velocity. The NN allows maximum pitch velocity predictions using clinical measures that can be easily measured. Fastball gains can be projected based on strength increases to the NN inputs.

Some limitations of the current study should be acknowledged. The sample size was small (n=12), which may cause some differences between D and ND metrics to go undetected. Some subjects may have been apprehensive about full rotational ROM stretches. Effort level for the strength testing cannot be fully controlled, and some subjects may not have given maximum effort, especially during eccentric contractions. The order of measurements was not randomized, and subjects may have been more comfortable with the protocol on the second arm tested.

Future research should continue to investigate correlations between clinical measures and kinetics and pitch velocity. Correlations to clinical measures of strength and flexibility are valuable because they are easy to measure and can be improved through training. A higher subject population may allow for more significant differences and correlations to be found. Testing various skill levels of pitchers may also yield useful results. Future studies should also continue to investigate how correlations can be used to create NNs. A regression learner NNs that can predict elbow varus torque would be useful to quantify the torque without a biomechanical analysis.

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APPENDIX A: CONSENT FORM

Medical College of Wisconsin and Froedtert Hospital
CONSENT TO PARTICIPATE IN RESEARCH

Name of Study Subject: _____

Upper Extremity Biomechanics during a Baseball Pitch

Janelle Cross, PhD
Department of Orthopaedic Surgery
(414) 805-7119
Medical College of Wisconsin
8701 Watertown Plank Road
Milwaukee Wisconsin 53226

We are asking your permission to save some of your health information for research studies in the future. This form tells you what we would like to do and possible risks. If there is anything you do not understand, please ask questions. Then you can decide if you want to give your permission or not.

A1. WHAT IS BANKING AND WHAT IS A BANK?
"Banking" is storing health information and/or blood or tissue for future research studies. A "bank" is the place where it is stored.

A2. WHY IS THIS BANKING STUDY BEING DONE?
Janelle Cross, PhD wants your permission to bank your health information for future research. Janelle Cross, PhD would like you to take part in this bank because you have taken part in pitching analysis. In the future, other doctors and scientists at this and other medical and research centers may use your health information to learn about many different diseases and conditions. Their goal is to improve health and develop new treatments.

A3. DO I HAVE TO BANK MY HEALTH INFORMATION?
You are free to say yes or no. Your decision will not change your current or future health care.

B2. WHAT HEALTH INFORMATION WILL BE BANKED?
The health information we will collect and bank for this study is: Results of motion analyses, including the motions of your arms, legs and body, and other health information, such as previous injuries, strength tests, range of motion and functional movement screen scores.

B3. WHERE WILL MY HEALTH INFORMATION BE BANKED?
Janelle Cross, PhD will bank your health information at MCW/Froedtert Hospital along with samples of many other people.

C. WHAT RISKS OR PROBLEMS CAN I EXPECT FROM THE STUDY?

C2. Are there any risks to confidentiality in this banking study?
Your health information will be banked at MCW/Froedtert Hospital with a code so that only Janelle Cross, PhD and authorized members of the study team can link the health information with your personal identifiers. One risk of taking part in a research study is that more people will handle your personal health information. The study team will make every effort to protect the information and keep it confidential, but it is possible that an unauthorized person might see it. Depending on the kind of information being collected, it might be used in a way that could embarrass you. If some records include genetic information, it is against federal law (GINA) for health insurance companies to deny health insurance, or large employers to deny jobs, based on your genetic information. But the same law does not protect your ability to get disability, life, or long term care insurance. If you have questions, you can talk to the study doctor about whether this could apply to you.

C3. ARE THERE BENEFITS OF BANKING MY HEALTH INFORMATION?
There is no direct benefit to you. Other people might benefit if researchers learn more by using your banked health information.

D1. WHAT ARE THE COSTS OF BEING IN THE STUDY?
There are no costs to you or your insurance company for any of the procedures in this banking part of the study.

D2. WILL I BE PAID FOR BANKING MY HEALTH INFORMATION?
Your health information will be used only for research. Janelle Cross, PhD and MCW/Froedtert Hospital will not sell any of it. If money is made from their discoveries, you will not receive payment.

D3. WHAT HAPPENS IF I AM INJURED BECAUSE I TOOK PART IN THE STUDY?
If you have been following directions, the injury is directly related to the research, and not the result of an underlying condition, then MCW will compensate you for the injury.

If you think you have been injured because of this study, let the study doctors know right away by calling (414) 805 - 7119.

D4. WHO CAN ANSWER MY QUESTIONS ABOUT THE BANK?
- If you have more questions about this study at any time, you can call Janelle Cross, PhD at (414) 805 - 7119.
- If you have questions about your rights as a study participant, want to report any problems or complaints, obtain information about the study, or offer input, you can call the Medical College of Wisconsin/Froedtert Hospital Research Subject Advocate at 414-955-8844.

E1. WHO WILL SEE MY HEALTH INFORMATION?
The only MCW/Froedtert Hospital employees allowed to handle your health information are those on the study team, those on the Institutional Review Board (IRB) and those who check on the research activities to make sure the hospital's rules are followed.

If we share your health information with other research groups outside of MCW/Froedtert Hospital, your personal identifiers will be removed so that no one will know that it came from you.

We will not use your personal health information for a different study without your permission or the permission of a hospital research review board (IRB). Once all personal identification is removed, the information might be used or released for other purposes without asking you. Results of the study may be presented in public talks or written articles, but no information will be presented that identifies you.

E2. HOW LONG WILL MY HEALTH INFORMATION BE BANKED?
The purpose of the bank is to answer questions in the future, so we expect to keep your health information for a long time, maybe forever.

E3. CAN I REMOVE MY HEALTH INFORMATION ONCE IT IS BANKED?
Your health information is banked at MCW/Froedtert Hospital. If it is still identified as yours, you can have it removed or destroyed by contacting Janelle Cross, PhD in writing at 8700 Watertown Plank Road, Milwaukee, WI 53226.

CONSENT TO PARTICIPATE IN THE STUDY

By signing my name below, I confirm the following:

- I have read (or had read to me) this entire consent document. All of my questions have been answered to my satisfaction.
- The bank's purpose, procedures, risks and possible benefits have been explained to me.
- I agree to let the study team use and share the health information and other information gathered for this study.
- I voluntarily agree to participate in this research study. I agree to follow the study procedures as directed.
- At any time, I can ask the bank to stop collecting health information, and ask the bank to delete/destroy all my health information, if it is still identified as mine.

IMPORTANT: You will receive a signed and dated copy of this consent form. Please keep it where you can find it easily. It will help you remember what we discussed today.

EFFECTIVE
6-12-2018
MCW/FH IRB

Subject's Name *please print*	**Subject's Signature**	**Date**