Glenohumeral Stiffness in Overhead Athletes Following Pitching

THESIS

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Abstract

Experienced baseball pitchers exhibit differences in range of motion, strength, and stiffness of their glenohumeral joint between their dominant and non-dominant arms. These changes are attributed to the repetitive and ballistic demands of pitching. Immediate changes in range of motion and strength in the dominant arm following pitching have been reported. These changes have been correlated with shoulder injuries in pitchers. Active glenohumeral joint stiffness is the measure of the change in torque over a change in rotational angle during constant rotation. This project investigates if any changes in active glenohumeral joint stiffness occur as a result of pitching a simulated game, and whether any range of motion, strength, or kinematic parameters correlate with the differences before and after throwing. The hypothesis was that active glenohumeral joint stiffness would adaptively increase following throwing. 18 healthy subjects participated in this study, all of which had competed at the high school varsity level or higher. Active glenohumeral joint stiffness was recorded using a Biodex dynamometer and was calculated for two different rotational speeds, 90°/sec and 300°/sec. Subjects eccentrically loaded their external rotators during a constant internal rotation. Five range of motion measurements were taken: external rotation (ER), internal rotation (IR), horizontal adduction (HAD), low flexion (LF), and extension plus internal rotation (EIR). Both internal and external isometric strength were recorded with a handheld dynamometer, and passive rotational stiffness was calculated as well. Measurements
were taken before, immediately following, and 24 following a pitching session. Subjects threw 15 pitches every inning, for up to 7 innings or when they felt they could no longer continue due to fatigue. Results indicate that the active stiffness of the glenohumeral joint significantly decreases following a pitching session, from an average of 0.79 ± 0.24 ft-lbs/deg before throwing to averages of 0.55 ± 0.29 ft-lbs/deg and 0.48 ± 0.23 ft-lbs/deg immediately following and 24 hours following throwing, respectively. Decreases in external rotation strength and (18.96 ± 3.28 kgf before throwing, 17.02 ± 3.68 kgf immediately following throwing) and decreases in horizontal adduction range of motion (34.31 ± 6.72° before throwing, 31.08 ± 4.38° immediately following throwing) indicate that muscular properties are altered immediately following throwing. The low flexion range of motion test showed no statistically significant differences before and immediately after throwing (26.89 ± 6.05° to 29.27 ± 5.29°, respectively) which indicates that capsular changes do not occur immediately following throwing. From these results, the immediate decrease in active glenohumeral joint stiffness following throwing can be attributed to a change in the rotator cuff muscle properties.
Dedication

This document is dedicated to my friends and family.
Acknowledgments

I would like to thank my project advisor, Dr. John Borstad, for all of his help and support throughout the entire thesis process. I would also like to acknowledge Mike McNally and Jay Young for their assistance in setting up and analyzing the 3D motion capture data. Finally, I would like to thank my family and friends for their support over the past two years.
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Chapter 1: Introduction

Throwing athletes have high rates of shoulder pain due to the repetitive and ballistic demands of their sport. Based on epidemiological studies, researchers have found that between 29% and 35% of pitchers aged 9 to 19 experience shoulder pain, and that 38% of high school pitchers experience shoulder pain (Lyman, 2001; Olsen, 2006; Fleisig, 2010). Posner et al. found that 51.4% of all player injuries in Major League Baseball between 2002 and 2008 were attributed to upper extremity injuries, and 30.7% of injuries in pitchers were shoulder injuries (Posner, 2011). Shoulder injuries develop in pitchers due to repetitive throwing and are most commonly categorized as overuse injuries.

Pitching Mechanics

Several studies have analyzed the six stages of throwing: windup, early cocking, late cocking, acceleration, deceleration, and follow through, as shown in Figure 1 (Park, 2002; Escamilla, 2007; Wilk, 2009). The early phases offer minimal risk to cause injury (Park, 2002). Windup begins at the first movement of the pitcher until they remove the ball from the glove. The thrower uses a push off move to shift the center of gravity towards home plate. Moving into early cocking, the thrower rotates his body 90° while flexing both arms. The thrower keeps the trunk rotated back as far as possibly in order to generate the greatest amount of trunk rotation. Studies have found that the forces generated from step off and body rotation contribute up to 50% of the velocity of the
pitch (Toyoshima, 1974). Late cocking begins once the stride foot makes contact with the ground. Maximum external rotation of the shoulder is seen in this phase, with studies reporting values between 160° and 185° among professional baseball players (Park, 2002). During the late cocking phase, the arm is externally rotated over a total arc of about 125° (Park, 2002). Acceleration begins once the thrower moves his arm toward home plate. Here, large forces and rotational velocities are achieved through trunk and shoulder rotation. Rotational velocities of the thrower's arm as high as 9198°/sec and a mean maximum of 6180°/sec have been reported (Pappas, 1985). Mean maximum internal rotation velocities during acceleration have also been recorded by Dillman et al. (6940°/sec) and Feltner and Dapena (6100°/sec) (Dillman, 1993; Feltner, 1986).

Decelerating the arm is needed to absorb the high energy produced in the late cocking and acceleration phases. After ball release, the posterior shoulder is eccentrically loaded and the musculature has been found to experience deceleration values of -500,000°/sec² (Park, 2002). These large values observed during deceleration cause large forces and stresses on the posterior shoulder, which could lead to injuries when overused.

Figure 1: Stages of Throwing. A) Windup; B) Early Cocking; C) Late Cocking; D) Acceleration; E) Deceleration; F) Follow Through; (Park, 2002)
Shoulder Anatomy

In order to maximize function and limit injury, the glenohumeral joint must maintain a balance between both stability and mobility. The glenohumeral joint is comprised of several soft tissue components that help dissipate the kinetic energy of the throwing motion. The humeral head is about three times as large as the glenoid fossa, causing a lack of bony stability (Borsa, 2008). A fibrocartilage ring called the glenoid labrum deepens the concavity of the glenoid by 50%, helping limit glenohumeral joint translation (Borsa, 2008). Extending from the labrum to the humeral head, the joint capsule is a non-contractile tissue comprised of primarily Type I collagen. The capsule is represented in Figure 3. In addition to the capsule, the glenohumeral joint is also comprised of musculature to offer mobility and improve stability. The rotator cuff muscles include four deep muscles that connect the scapula to the humerus. The rotator cuff muscles are shown in Figure 2 and include the subscapularis, supraspinatus, infraspinatus, and teres minor, with the latter two as the primary external rotators (Fleisig, 1996). Other muscles that are used during throwing include the deltoid, rhomboid, trapezius and latissimus dorsi, especially during deceleration. The rotator cuff and scapular stabilizing muscles are used for dynamic motion restraint, while the capsule is thought to offer static restraint (Thomas, 2012).
Figure 2: Rotator Cuff Muscles (American Academy of Orthopaedic Surgeons, 2011)

Figure 3: Glenohumeral Joint Capsule (Gray, 2000)
Range of Motion

*Increases in External Rotation (ER)*

Baseball players in particular have well documented alterations in shoulder range of motion on their throwing shoulder, including increased external rotation and decreased internal rotation (Pappas, 1985; Brown, 1988; Crockett, 2002; Ellenbecker, 2002; Kibler, 2003; Borsa, 2006; Myers, 2006; Borsa, 2008; Dwelly, 2009; Wilk, 2009; Borstad, 2011). The increase in external rotation mobility is widely believed to allow overhead throwers to achieve higher ball velocities from the greater amount of external rotation in late cocking (Wilk, 2002; Borsa, 2006; Borsa, 2008). Microtrauma to the static and dynamic restraints of the glenohumeral joint contributes to the external rotation gains (Park, 2002; Myers, 2006).

*Decreases in Internal Rotation (IR)*

Decreased shoulder internal rotation range of motion has also been reported in baseball pitchers, and this loss of internal rotation range of motion is highly correlated with injury rates (Park, 2002; Wilk, 2009). Losses occur both immediately following pitching as well as over an entire season. The total loss of internal rotation has been recorded between 8-15° and is symmetrically offset by a total gain of external rotation in the 5-12° range (Borsa, 2002). Thus, the total rotational arc does not change when compared to the non-dominant arm, however is shifted in favor of external rotation (Wilk, 2002).
**Glenohumeral Internal Rotation Deficit (GIRD)**

In some throwers, there is more decrease of internal rotation than a gain of external rotation. This is referred to as glenohumeral internal rotation deficit (GIRD), and it is believed that throwers that experience GIRD are more at risk for injury (Myers, 2006; Wilk, 2009; Stanley, 2011; Wilk, 2011). Myers et al. found that throwers diagnosed with internal impingement have significantly more GIRD, as well as less horizontal adduction range of motion (Myers, 2006). The cause of the lost motion is based on changes to the posterior shoulder, yet researchers continue to debate whether the alterations are in the rotator cuff muscles or the capsule. Long term range of motion changes are attributed to the glenohumeral joint capsule, while the cause of immediate range of motion loss is believed to be caused by changes in muscular stiffness. Researchers believe that when the glenohumeral capsule becomes contracted, the humeral head shifts posterior and superior during late cocking, which entraps the articular side of the supraspinatus tendon between the humeral head and glenoid/labrum complex (Borstad, 2011). Capsule contracture is thought to contribute to the loss of internal rotation, and to the development of internal impingement in overhead athletes (Myers, 2006; Borstad, 2011).

**Retroversion**

Another change in the glenohumeral joint is an osseous adaption in the proximal growth plate of the humerus resulting in humeral retroversion (Ellenbecker, 2002; Borsa, 2006; Wilk, 2009). Retroversion is another factor that causes the thrower's mobility patterns to be altered. Researchers believe that this osseous adaptation occurs due to the
repetitive forces that are exerted on the humeral head, and that throwers experience this repetitive stress during youth baseball participation while growth plates are 'open' (Borsa, 2006). Increased retroversion in throwers increases external rotation and decreases internal rotation range of motion by equal amounts. Like the capsule, osseous changes occur over an extended period of throwing exposure prior to skeletal maturation.

Measurement Techniques

The most common method of measuring internal and external rotation in the glenohumeral joint is with the subject supine and the humerus abducted 90°. In addition to these two range of motion measurements, there are additional measurements that can be implemented in a clinical setting to further understand range of motion changes in throwers. One method that has been investigated recently is the low flexion test (LF), with the humerus flexed at 60°, the elbow flexed at 90°, and the arm rotated internally. Borstad et al. found that this test produced greater strain on the middle region of the posterior capsule that had been experimentally contracted ex vivo (Borstad, 2011). The LF test can be used to determine if the posterior capsule undergoes any significant changes immediately following pitching.

Another test that has been used by Laudner and Myers is the horizontal adduction test (HAD), with the subject supine. This test is highly correlated with supine internal rotation range of motion in overhead throwing athletes (Laudner, 2006; Myers, 2007; Borstad, 2011). There is debate between researchers as to whether the HAD test tracks muscular or capsular changes.
Another recently developed clinical test is the extension plus internal rotation test (EIR). The subject is standing with their arm extended at 60° and then internally rotated until the range of motion limit is reached. Dashottar et al. found that the EIR test was most influenced by changes in muscle passive tension of the external rotators, specifically infraspinatus (Dashottar, 2013).

**Active Glenohumeral Joint Stiffness**

The range of motion measurements offer insight into shoulder mobility and how it is affected by throwing, while stability can be analyzed from the stiffness of the glenohumeral joint. Rotational stiffness can be defined as the ratio between the change in torque to the change in position (Thomas, 2012). Active glenohumeral joint stiffness is measured as the change in torque produced by an eccentric loading of the external rotators over the change in position during a constant applied internal rotation (Thomas, 2012). During throwing, large amounts of rotational energy are absorbed during the deceleration phase. Previous studies have investigated the posterior capsule and believe that it can undergo adaptive changes due to the chronic eccentric loading during throwing, specifically in deceleration (Borsa, 2006; Poser, 2007; Thomas, 2012). These changes include a thickening of the posterior capsule, which could imply an increase in stiffness. Previous studies have investigated long term active stiffness changes in throwing athletes, yet immediate changes in stiffness have not yet been researched. Thomas et al. developed a method of measuring active joint stiffness in throwers and compared the dominant and non-dominant arms (Thomas, 2012). The thrower's arm was loaded eccentrically over a 20° arc, and the torque the subject produced over the arc was
measured. They found statistically significant changes between the dominant and non-dominant arm for active joint stiffness, with the dominant arm having increased stiffness. Additionally, a significant positive correlation between posterior capsule thickness as measured with ultrasound and active glenohumeral joint stiffness was found. The active glenohumeral joint stiffness in this study is comprised of both passive and dynamic components. The void in the study is that Thomas et al. did not distinguish between dynamic and static stiffness. The dynamic stiffness, or active stiffness, measures the contributions of both the musculature and capsular components of the glenohumeral joint (Thomas, 2012). Static stiffness measures how much rotation occurs after an applied torque. This measurement, also referred to as passive stiffness, measures only the static components of the glenohumeral joint. With both dynamic and static components comprising the glenohumeral joint, each play a role in the overall stiffness, and it is important to distinguish how changes in either component affect stiffness.

Alterations in glenohumeral stiffness could be a contributing or primary factor to shoulder injuries in throwers (Borsa, 2006; Poser, 2007; Thomas, 2012). Stiffness of the glenohumeral joint is an indicator of the dynamic ability to control the joint. While static components need to be included in the overall stiffness calculation, an immediate change in stiffness would correlate with changes in the dynamic stability components including the rotator cuff musculature. This differs from the static stability control that the capsule offers (Thomas, 2012). In order to distinguish whether changes occur in the dynamic or static components, the range of motion tests can be used to determine which components undergo immediate adaptations to throwing. The LF test is a primary test to monitor
capsule changes, while the EIR test is a musculature test (Borstad, 2011; Dashottar, 2013). Horizontal adduction is still debated between a test that would show changes in muscle or capsule (Laudner, 2006; Myers, 2007; Borstad, 2011). In this study, active stiffness is measured under eccentric loading of the external rotators, similar to the deceleration phase of throwing.

**Kinematics of Pitching**

With the well documented changes in range of motion and strength, as well as new insight into glenohumeral stiffness, researchers have investigated how pitching mechanics are correlated with these changes. Feltner and Dapena studied the kinematics and kinetics of collegiate pitchers using the direct linear transformation method of three-dimensional cinematography (Feltner, 1986). Their study helped set up the basis for capturing pitching biomechanics in three dimensions. Since Feltner and Dapena's study, motion capture has been used to analyze the biomechanics of pitching, and has been used to investigate how certain mechanics can lead to injuries (Feltner, 1986; Fleisig, 1995; Fleisig, 1996; Escamilla, 1998). Escamilla et al. were one of the first groups to investigate the effects of muscular fatigue on pitching biomechanics, and whether mechanics changed in late innings (Escamilla, 2007). They found that both ball velocity and forward trunk tilt were significantly lower in the final inning pitched compared to the first two innings of pitching (Escamilla, 2007). Studies have measured various kinematic properties during the early and late cocking and acceleration phases, but there is little research on the kinematics during the deceleration phase (Thurston, 1998; Murray, 2001; Mullaney, 2005).
Relationships between Parameters

In the current study, kinematic data was used along with range of motion, strength, and passive stiffness data to determine if there were any correlations or associations with a change in active stiffness at both 90°/sec and 300°/sec. Correlations were used to determine if any clinical measures could be used to identify subjects who would show larger decrease in active stiffness, and regression was used to determine if any clinical tests could be performed in the field to track changes in active stiffness. It was hypothesized that the kinematic parameters that would most likely show correlations with active stiffness would be peak horizontal adduction deceleration, peak internal rotation deceleration, peak active internal rotation, as well and baseline ER strength, baseline internal rotational passive stiffness, baseline LF, baseline HAD, and baseline EIR. Decreases in the change in active stiffness were hypothesized to be associated with a larger change in peak horizontal adduction deceleration, larger change in peak internal rotation deceleration, more baseline ER strength, baseline HAD, baseline EIR, and baseline IR passive stiffness. Larger decreases in active stiffness were also hypothesized to be associated with a smaller change in peak IR angle and lower baseline LF.

Objectives

Primary Objective

The main objective of this study was to identify if the active glenohumeral joint stiffness would change in baseball throwers immediately after throwing, as well as twenty-four hours following throwing. It was hypothesized that there would be increases in active glenohumeral joint stiffness immediately following throwing and 24 hours,
following throwing. The importance of an increase in active stiffness could show that immediate adaptations are needed as injury prevention mechanisms. Thomas et al. believed that adaptations occur in the glenohumeral joint to regulate the neuromuscular control system as well as enhance energy absorption capabilities during throwing (Thomas, 2012).

Secondary Objectives

Secondary objectives included identifying if any changes occurred in range of motion measurements, strength measurements, or passive stiffness measurements before and after throwing. It was hypothesized that there would be an immediate external rotation gain and internal rotation loss due to muscle fatigue, as well as a decrease in both HAD and EIR. No immediate change was expected for the LF test since the test was hypothesized to track capsular changes. The hypothesis was that there would be immediate decreases in both ER and IR strength, and that both ER and IR passive stiffness would immediately increase.

Third Objective

A third objective of this study was to determine if change in active stiffness following throwing can be correlated with or predicted by changes in strength, range of motion, passive stiffness, and pitching kinematics.
Chapter 2: Methods

Participants

Subjects were chosen to participate in this study if they were current collegiate pitchers or baseball players, or formerly played competitive baseball at the high school varsity level or higher. 18 subjects were tested. Subjects were excluded from this study if they had undergone shoulder or elbow surgery within the past 12 months, or had experienced pain or discomfort in their shoulder or elbow within the past 6 months. The subjects had a mean height and age of 71.8 ± 2.5 in, 24.2 ± 2.4 yrs, respectively. Subjects also had been removed from competitive baseball for a mean of 5.1 ± 1.8 yrs. Six subjects had been primarily pitchers, eight primarily played infield, two primarily played catcher, and two primarily played outfield. The study was approved by the Ohio State University Institutional Review Board and informed consent was obtained from participants prior to testing.

Procedure

The goal of this study was to measure active stiffness, range of motion, strength, and passive stiffness in baseball pitchers before, immediately following, and 24 hours following a pitching session. The four measurement tests are described in detail below, as well as a detailed procedure for the pitching session. Additionally, motion capture was used to collect kinematic data during pitching.
Active Glenohumeral Joint Stiffness

Active stiffness of the glenohumeral joint was measured first. Subjects were seated in a Biodex dynamometer and positioned so that their arm was abducted 90°, horizontally adducted 30°, and elbow flexed 90°. Two tests of reactive eccentric/eccentric rotation both internally and externally at speeds of 90°/sec and then 300°/sec were used. The Biodex dynamometer was programmed to force the subject into internal or external rotation, while the subject opposed the motion.

The maximum angles of internal and external rotation limits, which typically formed about a 90° arc, were set prior to testing. These limits were chosen to best represent the acceleration and deceleration phases of throwing. Subjects started at the external rotation limit. One repetition was defined as the Biodex first forcing the subject into internal rotation until the internal rotation limit was reached, and then forcing the subject into external rotation until the starting point was reached. Subjects initiated the movement by exerting an opposing force of at least 10 ft-lbs at each limit. Subjects were given verbal instructions about the testing protocol and up to three practice repetitions prior to collecting data. Five repetitions for each test were recorded, with a 10 second rest period between each test.

The torque and anatomical position (angle) data were plotted versus time for each rotational speed. Each repetition was isolated based on the anatomical position data. An average torque of the five repetitions was obtained and plotted against the anatomical position for each trial (before throwing, immediately following throwing, and 24 hours following throwing). The slopes over the first ten degrees of the torque versus position...
curves were used to define the active glenohumeral stiffness, in units of ft-lbs/deg. Peak torques were found for each trial, as well as the anatomical position at which they occurred. The angle was the amount of change in internal rotation from the vertical. Sample plots of the raw torque and position data versus time for the before throwing test and torque versus position for subject 1 are shown in Figure 4 and Figure 5. MATLAB was used to analyze the active stiffness data, and the code is attached in Appendix A.

Figure 4: Raw Torque and Position Data vs. Time - Subject 1
Range of Motion Measurements

Range of motion measurements were taken on the subjects using five different tests. The five tests included internal rotation (IR), external rotation (ER), horizontal adduction (HAD), low flexion (LF), and extension plus internal rotation (EIR). The order of these tests was the same order for all three sessions within each subject.

External Rotation and Internal Rotation

The subject lay supine on a bench and had their arm abducted 90° and their elbow flexed 90° for the IR and ER tests. Figure 6 shows the set up for both ER and IR. The Principal-Investigator (PI), Dr. John Borstad, ensured that the subject was relaxed and
was not resisting any applied movement. The subject's arm was either rotated internally (IR) to the limit where the scapula just began to come off of the bench or externally until the arm could no longer rotate (ER). The limits were recorded with a digital inclinometer (Baseline evaluation instruments, Fabrication enterprises Inc. White Plains, NY, USA), which was placed by the PI on the distal forearm. Values were recorded by the Co-Investigator (Co-I), Thomas Stoughton.

Figure 6: ER and IR Range of Motion Test Setup (Wilk, 2009)

*Horizontal Adduction (HAD)*

The HAD test required the subject to lie supine on the bench with their arm flexed at 90° and their elbow flexed at 90°. Figure 7 shows the test setup (Laudner, 2006). The PI positioned the subject's arm such that the scapula was at a 30° protraction angle. The PI moved the subject's relaxed arm horizontally across their body until the limit was
reached where the scapula just began to protract further than 30°. The PI used the digital inclinometer to measure the angle of the humerus from the vertical, keeping the inclinometer at the midpoint of the humerus. Values were recorded by the Co-I.

Figure 7: Horizontal Adduction (HAD) Range of Motion Test Setup (Laudner, 2006)

**Low Flexion (LF) and Extension plus Internal Rotation (EIR)**

The LF and EIR tests required the subject to stand. Subjects flexed their arm at 60° and flexed their elbow at 90° for LF. The PI rotated the subject's relaxed arm internally to its limit and the PI used the digital inclinometer to measure the angle from the horizontal by placing the inclinometer on the distal forearm. For EIR, the subjects arm was abducted at 60° and their elbow flexed at 90°. The PI rotated the subject's relaxed arm internally until its limit was reached and measured the angle of the forearm
from the horizontal using the digital inclinometer by placing it on the subject's distal forearm. Values were recorded by the Co-I.

*Strength Measurements*

Two strength tests were performed including internal rotation strength (IRS) and external rotation strength (ERS). For both tests, subjects were lying supine with their arms starting at a position of 90° abduction and their elbows flexed at 90° as seen in Figure 6 above. The subject began at a slight internal rotation during the ERS test and a slight external rotation for the IRS test. The PI placed the handheld dynamometer (Lafayette instruments Co., IN, USA) at the wrist, and instructed the subject to attempt to rotate their arm either internally or externally. The PI held the dynamometer at the subject's wrist and tried to force the arm into further rotation while the subject resisted the motion. The dynamometer recorded the maximum force in kilograms that was produced during the test. Each of the tests were performed twice and recorded on the data sheet by the Co-I, with 30 seconds of rest given between each trial, and a one minute rest given between the IRS and ERS tests.

*Passive Stiffness Measurements*

Passive stiffness was measured in each subject's shoulder both internally and externally. The internal rotation passive stiffness (IRPS) test and external rotation passive stiffness (ERPS) tests both required the subject to start initially lying supine on the bench, with their arms abducted 90° and their elbows flexed at 90°. The Co-I assisted in bringing the subject's arm to its internal or external range of motion limit using the same procedure as described above for range of motion. Next, the Co-I placed the
handheld dynamometer on the subject's wrist and applied a gradually increasing force such that the subject's arm continued to rotate past the limit. Once 2 kg of force was applied, the PI used the digital inclinometer to record the angle of the forearm from the horizontal. Each test was performed twice and recorded on the data sheet, with 30 second rests given between each trial. The angle recorded during the measurements was subtracted by the internal and external range of motion limits, to obtain the total change in arc produced by the 2 kgf applied force. Passive stiffness is inversely proportional to the total change in angle. Passive rotational stiffness was defined as the change in torque divided by the change in angle. The torque was first calculated from the applied force of 2 kgf and calculating the average forearm length as 15.7% of the subject's body height, and then dividing by the change in angle (Plagenhoef, 1983). Additionally, an average forearm angle of 15° was added to the change of angle, since the range of motion measurement recorded the angle on top of the forearm, while the passive stiffness measurement recorded the angle below the forearm. A sample calculation of passive stiffness is shown below for subject 1.

\[
\text{Passive Stiffness} = \frac{\Delta \text{Torque}}{\Delta \text{Angle}}
\]

\[
d = \text{Forearm length} = \text{Height} \times 0.157 = 71\text{in} \times 0.157 \times 0.0254 \frac{\text{m}}{\text{in}} = 0.283\text{m}
\]

\[
\Delta \text{Torque} = F \times d - 0 = 2\text{kg} \times 9.81 \frac{\text{N}}{\text{kg}} \times 0.283\text{m} - 0 = 5.56\text{Nm}
\]

\[
\Delta \text{Angle} = \text{ERPS} - \text{ER} + \text{Forearm Angle} = 116.0° - 89.4° + 15° = 41.6°
\]

\[= 0.726\text{ rad}\]

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Kinematics of Pitching

After stiffness and motion measurements, subjects were prepared for motion capture analysis of a pitching session. Reflective markers were placed on anatomical landmarks of the total body. Four markers were placed on the head, labeled right front head, left front head, right back head, and left back head. Markers on the trunk were placed at the C7 and T10 vertebrae, as well as the sternal notch and xyphoid process. The acromioclavicular (AC) joint, acromial angle, medial boarder of the spine of scapula, inferior angle, and coracoid process contained markers bilaterally. Each arm had markers at the medial and lateral wrist, medial and lateral epicondyle, mid-forearm, mid-upper arm, and third metacarpal-phalangeal joint. Markers were placed on the pelvis at both the ASIS and PSIS. Finally, each leg had markers located at the medial and lateral femoral condyle, medial and lateral malleolus, mid-anterolateral thigh and tibia, heel, the second metatarsal phalangeal joint, and the fifth metacarpal phalangeal joint. Figure 8 shows the marker locations described above. The location of the glenohumeral joint center and hip joint center were estimated using regression (Meskers, 1998; Davis, 1991).
**Pitching Session**

The subject was allowed up to a 15 minute warm-up prior to pitching. The pitching session was created to simulate a real pitching game, with the subject throwing up to 15 pitches per half inning for up to 7 half-innings. After each half-inning, the subject was asked to report their overall rating of perceived exertion using a Borg scale from 0-10 (Borg, 1998). The pitching session ended if the subject felt they could no longer pitch due to fatigue, or if they had pitched 105 pitches. Three subjects pitched only 90 pitches, and fifteen subjects pitched 105 pitches.
Data Collection

During the pitching session, motion capture data were collected for the entire first inning and only the last five pitches of each additional half-inning. The subject was measured for active stiffness, range of motion, strength, and passive stiffness in the same order and using the same procedure immediately following pitching, and again 24 hours following pitching.

Seven kinematic parameters were analyzed from the motion capture data. The capture system was a 10 camera Vicon MX40 (Vicon, Oxford, UK) passive optical motion capture system that recorded kinematic data at 300 Hz. All collections had been calibrated previously, so individual marker error for each camera was <0.2 mm. Data was processed in Visual3D (C-Motion, inc., Germantown, MD). Maximum active external rotation at late cocking, maximum active internal rotation, both internal rotation and horizontal adduction velocities during the acceleration phase, peak forward trunk tilt angle, and both peak internal rotation and peak horizontal adduction deceleration velocities between ball release to peak internal rotation were recorded for the last five pitches of the first inning, and the first 3 recorded pitches of the last inning pitched. Figure 9 shows the angle convention used for the kinematic parameters. Kinematic parameters were calculated as Euler angles using Visual3D. Elbow and wrist used X-Y-Z order (sagittal, frontal, transverse) with respect to the proximal segment. Trunk used X-Y-Z order with respect to the lab, and shoulder used Z-Y-Z (plane of elevation, elevation, long axis rotation) order with respect to the trunk (Lu, 1999). Inverse kinematics was used to constrain the elbow to 2 degrees of freedom (flexion/extension...
and pronation/supination) and constrain the wrist to 2 degrees of freedom (flexion/extension and radial/ulnar deviation). Results were analyzed using repeated measures analysis of variance to compare the average values of the final inning pitches to the average values of the first inning pitches.

![Kinematic Angle Convention](image)

Figure 9: Kinematic Angle Convention. Left: External Rotation (negative), Internal Rotation (positive); Center: Horizontal Adduction (positive); Right: Forward Trunk Tilt. (Escamilla, 2007)

**Statistical Analyses**

Means of the two measurements for each session for the range of motion, strength, and passive stiffness tests were calculated. The means were analyzed individually using a one-factor repeated measures analysis of variance (ANOVA) against time. Similarly, the active stiffness was calculated using custom MATLAB code (Appendix A), and a one-factor (time) repeated measures ANOVA was used to analyze the active stiffness at both 90°/sec and 300°/sec. An alpha of 0.05 was used for each analysis. Post-hoc repeated measures ANOVA tests between each trial (Pre, Post, and
Post24) were reported for tests that showed significant main effects. Bivariate correlations were used to determine if any significant correlations existed between the kinematic parameters and the change in active stiffness immediately following throwing compared to before throwing. Pearson's correlation coefficient and a two-tailed test of significance were computed. Multiple regression analysis was run with the dependent variables set as the change in active stiffness for 90°/sec and 300°/sec, and the independent variables were the change in peak horizontal adduction deceleration, change in peak IR deceleration, change in peak IR angle, baseline ER strength, baseline HAD, baseline EIR, baseline LF, and baseline IR passive stiffness. It should be noted that two subjects did not return for the measurements at 24 hours following throwing, and their results from immediately following throwing were carried through to complete the analysis. Separate statistical analyses confirmed that this did not significantly alter the results.
Chapter 3: Results

Active Stiffness

Active glenohumeral stiffness immediately following throwing and 24 hours following throwing was significantly less compared to just before throwing, at both 90°/sec (p = 0.001) and 300°/sec (p < 0.001). Table 1 presents the data for active glenohumeral stiffness at both 90°/sec and 300°/sec. Main effect p-levels (probability) and statistical power (sensitivity) for active stiffness as well as range of motion, strength, and passive stiffness tests are reported in Table 2, and post-hoc ANOVA tests for each time comparison are shown in Table 3. At 90°/sec, the active external rotational stiffness decreased from 0.79 ± 0.24 ft-lbs/deg before throwing to 0.55 ± 0.29 ft-lbs/deg immediately following throwing, and decreased to 0.48 ± 0.23 ft-lbs/deg 24 hours following throwing. When recording the active stiffness at a rate of 300°/sec, the same trends were observed, with the average stiffness before throwing was recorded at 0.76 ± 0.20 ft-lbs/deg, and the stiffness's immediately following throwing and 24 hours following throwing were 0.51 ± 0.22 ft-lbs/deg and 0.50 ± 0.22 ft-lbs/deg, respectively.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before Throwing</th>
<th>Immediately Following Throwing</th>
<th>24 Hours Following Throwing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active External Rotational Stiffness at 90°/sec</td>
<td>0.79 ± 0.24</td>
<td>0.55 ± 0.29*</td>
<td>0.48 ± 0.23*</td>
</tr>
<tr>
<td>Active External Rotational Stiffness at 300°/sec</td>
<td>0.76 ± 0.20</td>
<td>0.51 ± 0.22*</td>
<td>0.50 ± 0.22*</td>
</tr>
</tbody>
</table>

*Indicates a significant difference from Before Throwing

Table 1: Active External Rotational Stiffness (Mean, Ft-lbs/deg)
Table 2: P-level and Statistical Power for ROM, Strength, Passive and Active Stiffness

<table>
<thead>
<tr>
<th>Variable</th>
<th>P-Level (Alpha = 0.05)</th>
<th>Power (Sensitivity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Rotation (ER)</td>
<td>0.997</td>
<td>0.050</td>
</tr>
<tr>
<td>Internal Rotation (IR)</td>
<td>0.647</td>
<td>0.115</td>
</tr>
<tr>
<td>Low Flexion (LF)</td>
<td>0.355</td>
<td>0.220</td>
</tr>
<tr>
<td>Horizontal Adduction (HAD)</td>
<td>0.007*</td>
<td>0.839</td>
</tr>
<tr>
<td>Extension plus Internal Rotation (EIR)</td>
<td>0.191</td>
<td>0.338</td>
</tr>
<tr>
<td>Internal Rotation Strength</td>
<td>&lt; 0.001*</td>
<td>0.999</td>
</tr>
<tr>
<td>External Rotation Strength</td>
<td>0.004*</td>
<td>0.879</td>
</tr>
<tr>
<td>Calculated Internal Rotation Passive Stiffness</td>
<td>0.428</td>
<td>0.187</td>
</tr>
<tr>
<td>Calculated External Rotation Passive Stiffness</td>
<td>0.236</td>
<td>0.298</td>
</tr>
<tr>
<td>Active Stiffness at 90°/sec</td>
<td>0.001*</td>
<td>0.956</td>
</tr>
<tr>
<td>Active Stiffness at 300°/sec</td>
<td>&lt; 0.001*</td>
<td>0.984</td>
</tr>
<tr>
<td>Peak Torque at 90°/sec</td>
<td>&lt; 0.001*</td>
<td>0.999</td>
</tr>
<tr>
<td>Angle at Peak Torque at 90°/sec</td>
<td>0.031*</td>
<td>0.659</td>
</tr>
<tr>
<td>Peak Torque at 300°/sec</td>
<td>&lt; 0.001*</td>
<td>0.991</td>
</tr>
<tr>
<td>Angle at Peak Torque at 300°/sec</td>
<td>0.168</td>
<td>0.364</td>
</tr>
</tbody>
</table>

*Term significant at alpha = 0.05

Table 3: P-level and Statistical Power Between Each Time Trial

<table>
<thead>
<tr>
<th>Variable</th>
<th>Between Pre and Post</th>
<th>Between Pre and Post24</th>
<th>Between Post and Post24</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-Level (Alpha = 0.05)</td>
<td>Power (Sensitivity)</td>
<td>P-Level (Alpha = 0.05)</td>
</tr>
<tr>
<td>Horizontal Adduction (HAD)</td>
<td>0.039*</td>
<td>0.561</td>
<td>0.007*</td>
</tr>
<tr>
<td>Internal Rotation Strength</td>
<td>&lt; 0.001*</td>
<td>0.997</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>External Rotation Strength</td>
<td>0.006*</td>
<td>0.847</td>
<td>0.03*</td>
</tr>
<tr>
<td>Active Stiffness at 90°/sec</td>
<td>0.007*</td>
<td>0.818</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Active Stiffness at 300°/sec</td>
<td>&lt; 0.001*</td>
<td>0.998</td>
<td>0.003*</td>
</tr>
<tr>
<td>Peak Torque at 90°/sec</td>
<td>&lt; 0.001*</td>
<td>0.999</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Angle at Peak Torque at 90°/sec</td>
<td>0.099</td>
<td>0.377</td>
<td>0.018*</td>
</tr>
<tr>
<td>Peak Torque at 300°/sec</td>
<td>&lt; 0.001*</td>
<td>0.995</td>
<td>0.002*</td>
</tr>
</tbody>
</table>

*Term significant at alpha = 0.05

The means for peak torque and angle at which peak torque was achieved are shown in Table 4. Before throwing, subjects generated an average of 29.96 ± 4.05 ft-lbs of torque during eccentric loading of the external rotators. Peak torque generated before
throwing was significantly different than both peak torque generated immediately following throwing and peak torque generated 24 hours following throwing (p < 0.001 for both). An immediate average decrease of 5.03 ft-lbs after throwing at 90°/sec was observed compared to before throwing and an immediate decrease of 5.18 ft-lb after throwing was observed at 300°/sec compared to before throwing.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before Throwing</th>
<th>Immediately Following Throwing</th>
<th>24 Hours Following Throwing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Torque at 90°/sec (ft-lbs)</td>
<td>29.96 ± 4.05</td>
<td>24.93 ± 4.57*</td>
<td>22.93 ± 2.41*</td>
</tr>
<tr>
<td>Angle at Peak Torque at 90°/sec (degrees)</td>
<td>34.29 ± 22.68</td>
<td>24.63 ± 18.93</td>
<td>20.05 ± 15.93*</td>
</tr>
<tr>
<td>Peak Torque at 300°/sec (ft-lbs)</td>
<td>29.52 ± 5.44</td>
<td>24.34 ± 4.51*</td>
<td>23.49 ± 4.62*</td>
</tr>
<tr>
<td>Angle at Peak Torque at 300°/sec (degrees)</td>
<td>27.20 ± 11.68</td>
<td>21.34 ± 13.14</td>
<td>21.83 ± 15.64</td>
</tr>
</tbody>
</table>

*Indicates a significant difference from Before Throwing

Table 4: Peak Torque and Angle Data (Mean)

The angle at which the peak torque occurred for the 90°/sec trial before throwing compared to 24 hours following throwing were significantly different (p = 0.031).

Before throwing, subjects generated their peak torque after rotating their arms an average of 34.29 ± 22.68°. A day after throwing, subjects generated their maximum torque after only rotating their arms an average of 20.05 ± 15.93°. Although there was no statistical significance between the 300°/sec trial (p = 0.168), the trend was also that the subjects generated the maximum torque earlier during rotation after throwing than compared to before throwing.
Correlations

Correlations between the change in active stiffness and certain kinematic parameters, range of motion, strength, and passive stiffness measurements were analyzed. Table 5 and Table 6 provide Pearson correlations between active stiffness at both 90°/sec and 300°/sec and the following parameters: change in peak horizontal adduction deceleration, change in peak internal rotation deceleration, change in peak active internal rotation, baseline ER strength, baseline internal rotational passive stiffness, baseline LF, baseline HAD, and baseline EIR. The statistical significance of the correlations among all variables is also reported in Table 5 and Table 6. No statistically significant correlations were found.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Active Stiffness at 90°/sec</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pearson Correlation</td>
<td>P-level (2-tailed)</td>
</tr>
<tr>
<td>Change in Peak Horizontal Adduction Deceleration</td>
<td>-.332</td>
<td>.178</td>
</tr>
<tr>
<td>Change in Peak Internal Rotation Deceleration</td>
<td>-.152</td>
<td>.547</td>
</tr>
<tr>
<td>Change in Peak Active Internal Rotation Angle</td>
<td>.332</td>
<td>.179</td>
</tr>
<tr>
<td>Baseline ER Strength</td>
<td>-.329</td>
<td>.183</td>
</tr>
<tr>
<td>Baseline Internal Rotational Passive Stiffness</td>
<td>-.043</td>
<td>.864</td>
</tr>
<tr>
<td>Baseline LF ROM</td>
<td>-.181</td>
<td>.471</td>
</tr>
<tr>
<td>Baseline HAD ROM</td>
<td>-.224</td>
<td>.371</td>
</tr>
<tr>
<td>Baseline EIR ROM</td>
<td>.296</td>
<td>.232</td>
</tr>
</tbody>
</table>

Table 5: P-level and Statistical Power for Correlations with Change in Active Stiffness at 90°/sec
Table 6: P-level and Statistical Power for Correlations with Change in Active Stiffness at 300°/sec

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pearson Correlation</th>
<th>P-level (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Peak Horizontal Adduction Deceleration</td>
<td>-.079</td>
<td>.754</td>
</tr>
<tr>
<td>Change in Peak Internal Rotation Deceleration</td>
<td>-.136</td>
<td>.591</td>
</tr>
<tr>
<td>Change in Peak Active Internal Rotation Angle</td>
<td>.057</td>
<td>.823</td>
</tr>
<tr>
<td>Baseline ER Strength</td>
<td>.104</td>
<td>.682</td>
</tr>
<tr>
<td>Baseline Internal Rotational Passive Stiffness</td>
<td>-.132</td>
<td>.602</td>
</tr>
<tr>
<td>Baseline LF ROM</td>
<td>.189</td>
<td>.452</td>
</tr>
<tr>
<td>Baseline HAD ROM</td>
<td>-.326</td>
<td>.187</td>
</tr>
<tr>
<td>Baseline EIR ROM</td>
<td>.328</td>
<td>.184</td>
</tr>
</tbody>
</table>

Regression

Multiple regression analysis was used to determine if any parameters could predict the change in active stiffness for either 90°/sec or 300°/sec. Table 7 and Table 8 provide regression coefficients with the change in active stiffness at both 90°/sec and 300°/sec as the dependent variables and the following parameters as the independent variables: change in peak horizontal adduction deceleration, change in peak IR deceleration, change in peak active IR angle, baseline ER strength, baseline IR passive stiffness, baseline LF, baseline HAD, and baseline EIR. The statistical significance (p-level) of the regressions among all variables is also reported in Table 7 and Table 8. The only statistically significant relationship found was baseline ER strength (p = 0.026) with a regression coefficient of – 0.008.
Table 7: P-level for Regression with Change in Active Stiffness at 90°/sec

<table>
<thead>
<tr>
<th>Variable</th>
<th>Regression Coefficient</th>
<th>P-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Peak Horizontal Adduction Deceleration</td>
<td>.003</td>
<td>.226</td>
</tr>
<tr>
<td>Change in Peak Internal Rotation Deceleration</td>
<td>-.081</td>
<td>.197</td>
</tr>
<tr>
<td>Change in Peak Active Internal Rotation Angle</td>
<td>.039</td>
<td>.456</td>
</tr>
<tr>
<td>Baseline ER Strength</td>
<td>-.008</td>
<td>0.026*</td>
</tr>
<tr>
<td>Baseline Internal Rotational Passive Stiffness</td>
<td>-.009</td>
<td>.129</td>
</tr>
<tr>
<td>Baseline LF ROM</td>
<td>.000</td>
<td>.558</td>
</tr>
<tr>
<td>Baseline HAD ROM</td>
<td>-.009</td>
<td>.129</td>
</tr>
<tr>
<td>Baseline EIR ROM</td>
<td>-.010</td>
<td>.614</td>
</tr>
</tbody>
</table>

*Term significant at alpha = 0.05

Table 8: P-level for Regression with Change in Active Stiffness at 300°/sec

<table>
<thead>
<tr>
<th>Variable</th>
<th>Regression Coefficient</th>
<th>P-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Peak Horizontal Adduction Deceleration</td>
<td>.000</td>
<td>.318</td>
</tr>
<tr>
<td>Change in Peak Internal Rotation Deceleration</td>
<td>-.007</td>
<td>.551</td>
</tr>
<tr>
<td>Change in Peak Active Internal Rotation Angle</td>
<td>-.017</td>
<td>.387</td>
</tr>
<tr>
<td>Baseline ER Strength</td>
<td>-.055</td>
<td>.217</td>
</tr>
<tr>
<td>Baseline Internal Rotational Passive Stiffness</td>
<td>-.014</td>
<td>.098</td>
</tr>
<tr>
<td>Baseline LF ROM</td>
<td>.029</td>
<td>.219</td>
</tr>
<tr>
<td>Baseline HAD ROM</td>
<td>.025</td>
<td>.476</td>
</tr>
<tr>
<td>Baseline EIR ROM</td>
<td>.002</td>
<td>.795</td>
</tr>
</tbody>
</table>

Range of Motion

Table 9 shows the mean data for the five range of motion measurements. There was a significant decrease (p = 0.007) in HAD immediately following throwing and 24 hours following throwing compared to before throwing. Before throwing, the average angle of HAD was 34.31 ± 6.72°, which decreased by 3.23° immediately following throwing. The average HAD for 24 hours following throwing was recorded as 30.19 ± 5.07°. The other four tests showed no statistically significant changes between trials.
Internal rotation showed no change (p = 0.647) immediately following and 24 hours following pitching. External rotation stayed consistent between trials as well (p = 0.997). As expected, the LF test showed no statistical difference (p = 0.355) both immediately following and 24 hours following throwing. The changes in EIR were not statistically different (p = 0.191).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before Throwing</th>
<th>Immediately Following Throwing</th>
<th>24 Hours Following Throwing</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Rotation (ER)</td>
<td>101.49 ± 10.34</td>
<td>100.82 ± 10.54</td>
<td>100.56 ± 8.71</td>
</tr>
<tr>
<td>Internal Rotation (IR)</td>
<td>48.28 ± 9.01</td>
<td>49.83 ± 11.61</td>
<td>49.80 ± 11.79</td>
</tr>
<tr>
<td>Low Flexion (LF)</td>
<td>26.89 ± 6.05</td>
<td>29.27 ± 5.29</td>
<td>28.49 ± 7.20</td>
</tr>
<tr>
<td>Horizontal Adduction (HAD)</td>
<td>34.31 ± 6.72</td>
<td>31.08 ± 4.38*</td>
<td>30.19 ± 5.07*</td>
</tr>
<tr>
<td>Extension plus Internal Rotation (EIR)</td>
<td>43.98 ± 12.73</td>
<td>47.82 ± 9.14</td>
<td>46.39 ± 10.60</td>
</tr>
</tbody>
</table>

*Indicates a significant difference from Before Throwing

Table 9: Range of Motion Measurements (Mean, degrees)

Strength

Mean strength data is included in Table 10. There was a significant decrease (p < 0.001) in internal rotation strength immediately following throwing and 24 hours following throwing compared to before throwing. Immediately following throwing, the average loss of strength was 2.48 kgf. 24 hours following pitching, subjects, on average, increased strength by 0.22 kgf compared immediately following throwing. There was also a significant decrease (p = 0.004) in external rotation strength immediately following throwing compared to before throwing. Immediately following throwing, the average decrease in strength was 1.94 kgf compare to before throwing, followed by a slight increase of 0.57 kgf 24 hours after throwing.
Table 10: Strength (Mean, kgf)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before Throwing</th>
<th>Immediately Following Throwing</th>
<th>24 Hours Following Throwing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Rotation Strength (IR)</td>
<td>16.28 ± 3.31</td>
<td>13.80 ± 3.20*</td>
<td>14.02 ± 3.37*</td>
</tr>
<tr>
<td>External Rotation Strength (ER)</td>
<td>18.96 ± 3.28</td>
<td>17.02 ± 3.68*</td>
<td>17.59 ± 3.22</td>
</tr>
</tbody>
</table>

*Indicates a significant difference from Before Throwing

Table 11: Change of Rotation Angle Due to 2 kgf Applied Force (Mean, degrees)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before Throwing</th>
<th>Immediately Following Throwing</th>
<th>24 Hours Following Throwing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change of Internal Rotation</td>
<td>19.08 ± 16.45</td>
<td>17.56 ± 11.88</td>
<td>12.64 ± 14.29</td>
</tr>
<tr>
<td>(Passive Stiffness)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change of External Rotation</td>
<td>7.90 ± 10.31</td>
<td>8.12 ± 7.13</td>
<td>4.03 ± 6.49</td>
</tr>
<tr>
<td>(Passive Stiffness)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12: Calculated Passive Stiffness (Mean, Nm/rad)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before Throwing</th>
<th>Immediately Following Throwing</th>
<th>24 Hours Following Throwing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated Internal Rotation</td>
<td>12.01 ± 10.27</td>
<td>11.05 ± 4.26</td>
<td>15.30 ± 11.96</td>
</tr>
<tr>
<td>Passive Stiffness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculated External Rotation</td>
<td>17.12 ± 7.95</td>
<td>15.80 ± 5.57</td>
<td>24.62 ± 31.31</td>
</tr>
<tr>
<td>Passive Stiffness</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Passive Stiffness

There were no significant changes in internal or external rotational passive stiffness (p = 0.428, p = 0.236), respectively. Data for passive stiffness is shown in Table 11. The calculated passive stiffness is shown in Table 12. No statistically significant differences were found.
Kinematics

Seven kinematic parameters were evaluated from the data collected during pitching. Averages for the final five pitches of the first inning and averages of the first three recorded pitches of the final inning for these kinematic parameters are shown in Table 13. Significance and power levels of each kinematic parameter based on the repeated measures ANOVA are presented in Table 14. No statistically significant differences were found.

<table>
<thead>
<tr>
<th>Variable</th>
<th>First Inning</th>
<th>Last Inning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Active External Rotation (deg)</td>
<td>-147.26 ± 9.16</td>
<td>-146.51 ± 12.19</td>
</tr>
<tr>
<td>Maximum Active Internal Rotation (deg)</td>
<td>2.04 ± 12.00</td>
<td>2.34 ± 11.48</td>
</tr>
<tr>
<td>Peak Horizontal Adduction Velocity (deg/sec)</td>
<td>297.84 ± 131.49</td>
<td>223.58 ± 184.19</td>
</tr>
<tr>
<td>Peak Horizontal Adduction Deceleration (deg/sec²)</td>
<td>-34687.63 ± 1264.59</td>
<td>-38433.66 ± 25602.4</td>
</tr>
<tr>
<td>Peak Internal Rotation Velocity (deg/sec)</td>
<td>3617.29 ± 458.10</td>
<td>3660.24 ± 441.67</td>
</tr>
<tr>
<td>Peak Internal Rotation Deceleration (deg/sec²)</td>
<td>-13.08 ± 15.03</td>
<td>-15.22 ± 19.72</td>
</tr>
<tr>
<td>Forward Trunk Tilt Angle at Ball Release (deg)</td>
<td>-21.08 ± 9.10</td>
<td>-23.24 ± 7.46</td>
</tr>
</tbody>
</table>

Table 13: Kinematic Data (Mean)

<table>
<thead>
<tr>
<th>Variable</th>
<th>P-Level (Alpha = 0.05)</th>
<th>Power (Sensitivity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Active External Rotation</td>
<td>0.718</td>
<td>0.064</td>
</tr>
<tr>
<td>Maximum Active Internal Rotation</td>
<td>0.861</td>
<td>0.053</td>
</tr>
<tr>
<td>Peak Horizontal Adduction Velocity</td>
<td>0.052</td>
<td>0.508</td>
</tr>
<tr>
<td>Peak Horizontal Adduction Deceleration</td>
<td>0.514</td>
<td>0.095</td>
</tr>
<tr>
<td>Peak Internal Rotation Velocity</td>
<td>0.461</td>
<td>0.109</td>
</tr>
<tr>
<td>Peak Internal Rotation Deceleration</td>
<td>0.291</td>
<td>0.175</td>
</tr>
<tr>
<td>Forward Trunk Tilt Angle at Ball Release</td>
<td>0.441</td>
<td>0.114</td>
</tr>
</tbody>
</table>

Table 14: P-level and Statistical Power for Kinematic Data
Borg Rating

Subjects reported their level of fatigue using a 0-10 Borg scale; with 0 being no fatigue and 10 being completely fatigued (Appendix B). After the first inning, subjects reported an average of 1.85 ± 1.31 on the Borg scale. After subjects threw their second to last inning, the scores increased to an average of 5.57 ± 1.27. After completing the pitching session, the average rating of fatigue was reported as 6.46 ± 1.38. The results of the Borg scores are tabulated in Table 15.

<table>
<thead>
<tr>
<th>Variable</th>
<th>First Inning</th>
<th>Second to Last Inning</th>
<th>Last Inning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borg Score</td>
<td>1.66 ± 1.24</td>
<td>5.39 ± 1.23</td>
<td>6.36 ± 1.27</td>
</tr>
</tbody>
</table>

Table 15: Borg Scores (Mean)
Chapter 4: Discussion

Active Glenohumeral Joint Stiffness Changes

The primary objective of the study was to analyze the active glenohumeral stiffness in overhead throwers immediately following pitching as well as 24 hours following pitching. This analysis showed that glenohumeral joint stiffness decreased immediately following throwing compared to before throwing, and decreased even more on average 24 hours after throwing compared to immediately following throwing. The analysis also showed that the maximum torque generated by the subjects decreased immediately following throwing compared to before throwing. Because subjects are repetitively contracting the external rotators eccentrically, it is logical that the maximum torque would decrease following throwing. Not surprisingly, external rotation isometric strength significantly decreased as well (Table 10). Additionally, after throwing, subjects were only able to generate the peak torque after less rotation, which could represent another loss of strength. After throwing, subjects experience muscle fatigue, shown by the decrease in both internal and external rotational isometric strength, the decrease in peak torque, and generating peak torque earlier during internal rotation. While fatigued, throwers may have difficulty generating enough torque to decelerate their arms, which could lead to altered joint loading conditions that may contribute to injury.

Thomas et al. found that active glenohumeral stiffness in overhead throwers was greater in the dominant arm compared to the non-dominant arm (Thomas, 2012). The
present study found that there was an immediate decrease in stiffness following throwing compared to before throwing. One hypothesis is that this decrease in stiffness is largely due to muscle fatigue, and that the subject is unable to generate as much torque following throwing due to a decrease in strength. Because the external rotators become fatigued during pitching, it is likely the posterior capsule gradually experiences a larger role in energy absorption during the deceleration phase. If this pattern is sustained over many games or seasons, the posterior capsule will likely begin to adaptively thicken to withstand the high forces during repetitive throwing. Because the posterior capsule thickens over time, glenohumeral stiffness would eventually increase due to capsular changes, yet this increase would also occur over a longer time period. Therefore, compared bilaterally with the non-dominant arm, overhead athletes would have a larger stiffness in the dominant arm (Thomas, 2012). In contrast, the decrease in active glenohumeral stiffness immediately following a pitching session can be attributed to muscle fatigue and the subsequent decrease in strength.

Correlations with Changes in Active Stiffness

Kinematic data from the throwing session, as well as some range of motion, strength, and passive stiffness data, were used to determine if any correlations existed between the active stiffness of the glenohumeral joint and these parameters. It was hypothesized that eight different parameters were the most likely to show correlations with the change in active stiffness. These parameters included a change in peak horizontal adduction deceleration, change in peak IR deceleration, peak active IR angle, baseline ER strength, baseline IR passive stiffness, baseline LF, baseline HAD, and
baseline EIR. The results show that there were no statistically significant correlations between the parameters and the change in active stiffness for either 90°/sec or 300°/sec.

Regression

The same parameters used in the correlation analysis were used to determine if they could predict the changes in active stiffness at either 90°/sec or 300°/sec. The measurement of active glenohumeral joint stiffness was found using a Biodex dynamometer. The Biodex dynamometer is unable to be used in field studies or practical applications, so the regression analysis was performed to determine which, if any, parameters could be used to predict the changes in active stiffness. The results show that baseline ER strength had a significant regression coefficient with the change in active stiffness at 90°/sec (Table 7). This indicates that ER strength could be used in the field to predict the change in active stiffness that the thrower would experience. As stated previously, the decrease in active glenohumeral joint stiffness is hypothesized to be due to a decrease in ER strength and the presence of muscle fatigue. The regression analysis supports this hypothesis in that ER strength would likely be the best tool in determining a decrease in the active stiffness. By tracking ER strength throughout a baseball game, it could be possible to predict decreases in active stiffness and help reduce the risk of injury by removing pitchers once a certain decrease of active stiffness is observed. Further research would be needed to determine a relationship between injury risks and changes in active stiffness. A larger sample size could potentially further help validate these results as well.
Range of Motion Changes

*Horizontal Adduction*

Range of motion measurements taken before and after throwing were used to evaluate the effect of a pitching session on the glenohumeral joint musculature and capsule. There were statistically significant differences in the HAD test after throwing. The HAD test is being debated as being a good measurement of capsular changes, versus being a good measurement for determining musculature changes (Launder, 2006; Myers, 2007; Borstad, 2011). The hypothesis was that this test was more of a measure for tracking musculature changes in the glenohumeral joint, and that there would be a change immediately following throwing compared to before throwing. Based on the results, the belief is that the HAD test should be used to track muscle changes.

*Extension plus Internal Rotation (EIR)*

The EIR test was another test that was hypothesized would show immediate changes following throwing because the EIR test is proposed to also be a good measure of tracking changes in the external rotator cuff muscles. The results showed no statistically significant changes in EIR following throwing. The EIR test has been shown to be a good measure of the external rotator cuff muscles, specifically infraspinatus (Dashottar, 2013). It could be that changes to the infraspinatus muscle differ across all subjects, which is why no statistical significance was observed. Also, it is possible that the active glenohumeral joint stiffness tests influenced some of the range of motion measurements. Since the active stiffness measurement was recorded first, subjects could have experienced a small but significant amount of fatigue prior to the range of motion...
tests. Therefore, the ability to observe a significant change in range of motion due to muscular changes would be difficult. Further research is recommended to analyze how EIR changes following throwing is a larger subject pool, as well as bilateral differences and differences following a whole season.

*External Rotation (ER) and Internal Rotation (IR)*

Interestingly, there were no statistically significant changes in either the ER or IR range of motion tests. As stated previously, there is typically a slight gain in ER along with a slight loss of IR immediately following pitching. One theory as to why no significant changes were observed could be that the subjects did not throw enough pitches to altered IR or ER range of motion. Previous studies that have had subjects throw simulated games have the subjects throw as many as 135 pitches, while this present study only reached 105 pitches (Escamilla, 2007). Subjects in the study were not current pitchers, so reaching the higher number of pitches without risking injury was not possible. Another theory could be that, as stated above, the active glenohumeral joint stiffness test influenced the range of motion measurements both immediately following throwing and 24 hours following throwing. Subjects were measured within ten minutes of their final pitch, which could have also influenced some of the range of motion measurements.

**Passive Stiffness Changes**

Passive stiffness measurements showed that there were no statistically significant changes before and after throwing. Increases in passive stiffness were expected, and this could be due to the order of testing.
Strength Changes

As expected, both internal and external isometric strength significantly decreased immediately following throwing compared to before throwing. The muscles used during throwing become fatigued, and as a direct result the strength of both the internal rotators and external rotators decreases. Also for both internal and external strength, there was a slight increase of strength 24 hours following pitching compared to immediately following pitching. After 24 hours, the muscles begin to rebuild, and this will cause a return to baseline strength. Neither internal nor external strength is regained fully 24 hours following pitching compared to before throwing. Overhead athletes would need to rest for a longer period of time following pitching to regain the strength exhibited before throwing.

Objectives

Primary Objective

The primary objective of this study was to identify if any changes to active glenohumeral joint stiffness were observed before and after throwing. The hypothesis was that there would be an immediate increase in active stiffness following throwing. Based on the results, there was actually an immediate decrease in active stiffness following throwing, and the active stiffness remained decreased 24 hours following throwing.

Secondary Objective

Secondary objectives included identifying if any changes occurred in range of motion measurements, strength measurements, or passive stiffness measurements before
and after throwing. Contrary to the hypothesis, there were no statistically significant changes in either ER or IR. As expected, HAD range of motion significantly decreased following throwing and LF did not significantly change. EIR showed no significant differences before and after throwing, contrary to the original hypothesis. Both IR and ER strength significantly decreased following throwing as expected; however no significant changes were observed before and after throwing for both IR and ER passive stiffness.

Third Objective

Finally, the last objective was to determine if any correlations existed between kinematic parameters, range of motion measurements, strength measurements and the change in active glenohumeral stiffness, or if any of these parameters could predict a change in active stiffness based on regression models. Results showed no significant correlations existed, and that ER strength showed a significant regression coefficient to the change in active stiffness at 90°/sec.

Conclusions

Based on the results of this study, there are a few conclusions that can be made. First, the immediate decrease in active glenohumeral joint stiffness following throwing can be attributed to changes in the rotator cuff musculature. Long term changes to active stiffness reported by another study can most likely be attributed to posterior capsule changes (Thomas, 2012). The HAD range of motion test showed that significant decreases occurred following throwing, which means that this test most likely tracks muscular changes rather than capsular changes. The LF test, on the other hand, showed
no significant changes following throwing, and therefore it can be concluded that this test best tracks capsular changes. The ER strength test could be a valuable test to perform in the field to predict decreases in active stiffness.

Limitations

18 subjects were analyzed for this study. Each subject had experience playing baseball at either the varsity high school or collegiate level. One limitation of the study is that the subjects were not current players, and had been removed from competitive baseball for a few years. Additionally, not every subject's primary position was a pitcher. The subject pool can still be argued to show a representative sample of overhead athletes based on their experience level. While the primary position was desired to be pitcher, position players have shown some of the same range of motion changes as seen in pitchers. Position players exhibit a gain of external rotation coupled with a loss of internal rotation, and have also been seen to have a thicker posterior capsule in their dominant arm compared to their non-dominant arm (Wilk, 2009).

Future research

Further research of active stiffness in the glenohumeral joint in overhead athletes is recommended. It would be interesting to acquire kinetic data from the motion capture data set to determine how forces or moments act on the glenohumeral joint, and compare these with the active stiffness measurements. The main goal of this study was to determine if active stiffness changes in throwers after pitching. Additional research with a larger sample size could determine if any further clinical measures could be used to predict changes in active stiffness. Since utilizing a Biodex dynamometer outside of a
lab is infeasible, determining clinical measures to predict changes in active stiffness would be very valuable to help reduce the risk of injuries in pitchers.

Additional kinematic and kinetic data could be analyzed, including lower extremity and other trunk parameters. Determining how active stiffness would change in other overhead sports such as tennis, volleyball, and football would serve as potential studies in the future. The main objective would be to determine if there was a change in active stiffness, and why there would be a change based on the demands of the sport. Researchers could also get into more injury prevention and rehabilitation methods based on how stiffness changes in different sports.
References


Appendix A: MATLAB code

%%The following code was used to analyze active glenohumeral stiffness in
%%throwers before, immediately after, and 24 hours after a pitching
%%session. This data was used for Tom Stoughton's Master's Thesis, 2013.

clear all; close all; clc;

%Read raw Excel data into MATLAB, based on user input of subject name and
%rotational rate. Subject ID is s01, s02, etc. and rotational rate is
%either 90 or 300.

subjID = input('Enter Subject ID\n\n','s');
rate = input('Enter Rotational rate (90 or 300)\n\n','s');
filename = [subjID '.xls'];
sheet = [subjID '_' rate];
sheetPOST = [subjID 'post_' rate];
sheetPOST24 = [subjID 'post24_' rate];
StiffnessFileName = 'Stiffness_Data';

%Pre
tspan = xlsread(filename,sheet,'B7:B2000');
torque_list = xlsread(filename,sheet,'C7:C2000');
pos_list = xlsread(filename,sheet,'E7:E2000');
vel_list = xlsread(filename,sheet,'F7:F2000');

%Post
tspanPOST = xlsread(filename,sheetPOST,'B7:B2000');
torque_listPOST = xlsread(filename,sheetPOST,'C7:C2000');
pos_listPOST = xlsread(filename,sheetPOST,'E7:E2000');
vel_listPOST = xlsread(filename,sheetPOST,'F7:F2000');

%Post 24
tspanPOST24 = xlsread(filename,sheetPOST24,'B7:B2000');
torque_listPOST24 = xlsread(filename,sheetPOST24,'C7:C2000');
pos_listPOST24 = xlsread(filename,sheetPOST24,'E7:E2000');
vel_listPOST24 = xlsread(filename,sheetPOST24,'F7:F2000');

%%
%%This code begins by plotting each test -- Pre, Post, and 24hrs Post -- versus time.
%%Initially, ginput is used to locate the timepoints where the position of each rep begins to change
%%The user must select between 3 and 5 reps. The user selects a location
%%close to where the position data begins to increase from the baseline of
%%each rep. Ginput is only using the x-coordinate of the ginput data. Once
%the 3-5 reps have been identified, the user will hit the return key and
%MATLAB will plot red circles at the time points it has selected for the
%beginning of each rep. Each rep ends at the maximum position point within
%2 seconds from the start of the rep. This is done for each trial (pre,
%post, and post24)
figure(1)
plot(tspan,torque_list,tspan,pos_list)
grid on
hold on
j = 1;
k = 1;
h = 1;
timeStampPos = [];
timeStampPosPOST = [];
timeStampPosPOST24 = [];
[xpoint,ypoint] = ginput;
if length(xpoint)>=1 && length(xpoint)<=4
    newtimepoint = round(xpoint./10);
    othermin = pos_list(newtimepoint);
    j = 1;
    for m=1:length(newtimepoint)
        for i = newtimepoint(m):newtimepoint(m)+20
            if pos_list(i)==othermin(m) && pos_list(i+1)==othermin(m)+1
                newtimeStampPos(j) = i;
                j=j+1;
            end
        end
    end
    plot(newtimeStampPos.*10,othermin,'ro')
timeStampPos = [timeStampPos newtimeStampPos];
timeStampPos = sort(timeStampPos);
elseif length(xpoint) == 5
    newtimepoint = round(xpoint./10);
    othermin = pos_list(newtimepoint);
    j = 1;
    for m=1:length(newtimepoint)
        for i = newtimepoint(m):newtimepoint(m)+20
            if pos_list(i)==othermin(m) && pos_list(i+1)==othermin(m)+1
                newtimeStampPos(j) = i;
                j=j+1;
            end
        end
    end
    plot(newtimeStampPos.*10,othermin,'ro')
timeStampPos = [newtimeStampPos];
timeStampPos = sort(timeStampPos);
end
reps = length(timeStampPos);
for i = 1:reps-1
\[\text{maxAngle(i),timeMaxAngle(i)} = \max(\text{pos_list}(\text{timeStampPos}(i):\text{timeStampPos}(i)+200));\]

\[\text{timeMaxAngle}(i) = \text{timeMaxAngle}(i) + \text{timeStampPos}(i) - 2;\]

end

endValue = \min([\text{timeStampPos}(\text{reps})+250 \; \text{tspan}(\text{end})./10]);
\[\text{[maxAngle(reps),timeMaxAngle(reps)]} = \max(\text{pos_list}(\text{timeStampPos}(\text{reps}):\text{endValue}));\]

\[\text{timeMaxAngle}(\text{reps}) = \text{timeMaxAngle}(\text{reps}) + \text{timeStampPos}(\text{reps}) - 2;\]

figure(2)
plot(tspanPOST,torque_listPOST,tspanPOST,pos_listPOST)
grid on
hold on
[xpoint,ypoint] = ginput;
if length(xpoint)>=1 && length(xpoint)<=4
newtimepointPOST = round(xpoint./10);
otherminPOST = pos_listPOST(newtimepointPOST);
j = 1;
for m=1:length(newtimepointPOST)
    for i = newtimepointPOST(m):newtimepointPOST(m)+20
        if pos_listPOST(i)==otherminPOST(m) &&
            pos_listPOST(i+1)==otherminPOST(m)+1
            newtimeStampPosPOST(j) = i;
            j=j+1;
        end
    end
end
plot(newtimeStampPosPOST.*10,otherminPOST,'ro')
timeStampPosPOST = [newtimeStampPosPOST newtimeStampPosPOST];
timeStampPosPOST = sort(timeStampPosPOST);
elseif length(xpoint) == 5
newtimepointPOST = round(xpoint./10);
otherminPOST = pos_listPOST(newtimepointPOST);
j = 1;
for m=1:length(newtimepointPOST)
    for i = newtimepointPOST(m):newtimepointPOST(m)+20
        if pos_listPOST(i)==otherminPOST(m) &&
            pos_listPOST(i+1)==otherminPOST(m)+1
            newtimeStampPosPOST(j) = i;
            j=j+1;
        end
    end
end
plot(newtimeStampPosPOST.*10,otherminPOST,'ro')
timeStampPosPOST = [newtimeStampPosPOST];
timeStampPosPOST = sort(timeStampPosPOST);
end
reps = length(timeStampPosPOST);

for i = 1:reps-1
    \[\text{[maxAnglePOST(i),timeMaxAnglePOST(i)]} = \max(\text{pos_list}(\text{timeStampPosPOST}(i):\text{timeStampPosPOST}(i)+200));\]
    \[\text{timeMaxAnglePOST}(i) = \text{timeMaxAnglePOST}(i) + \text{timeStampPosPOST}(i) - 2;\]
end
endValuePOST = min([timeStampPosPOST(reps)+250 tsspanPOST(end)./10]);
[maxAnglePOST(reps),timeMaxAnglePOST(reps)] =
max(pos_listPOST(timeStampPosPOST(reps):endValuePOST));
timeMaxAnglePOST(reps) = timeMaxAnglePOST(reps)+timeStampPosPOST(reps)-
2;

figure(3)
plot(tspanPOST24,torque_listPOST24,tspanPOST24,pos_listPOST24)
grid on
hold on
[xpoint,ypoint] = ginput;
if length(xpoint)>1 && length(xpoint)<=4
    newtimepointPOST24 = round(xpoint./10);
    otherminPOST24 = pos_listPOST24(newtimepointPOST24);
    j = 1;
    for m=1:length(newtimepointPOST24)
        for i = newtimepointPOST24(m):newtimepointPOST24(m)+20
            if pos_listPOST24(i)==otherminPOST24(m) &&
            pos_listPOST24(i+1)==otherminPOST24(m)+1
                newtimeStampPosPOST24(j) = i;
                j=j+1;
            end
        end
    end
    plot(newtimeStampPosPOST24.*10,otherminPOST24,'ro'
    timeMaxAnglePOST24 = [timeMaxAnglePOST24(timeStampPosPOST24)];
timeMaxAnglePOST24 = sort(timeMaxAnglePOST24);
elseif length(xpoint) == 5
    newtimepointPOST24 = round(xpoint./10);
    otherminPOST24 = pos_listPOST24(newtimepointPOST24);
    j = 1;
    for m=1:length(newtimepointPOST24)
        for i = newtimepointPOST24(m):newtimepointPOST24(m)+20
            if pos_listPOST24(i)==otherminPOST24(m) &&
            pos_listPOST24(i+1)==otherminPOST24(m)+1
                newtimeStampPosPOST24(j) = i;
                j=j+1;
            end
        end
    end
    plot(newtimeStampPosPOST24.*10,otherminPOST24,'ro'
    timeMaxAnglePOST24 = [newtimeStampPosPOST24];
timeMaxAnglePOST24 = sort(timeMaxAnglePOST24);
end
reps = length(timeStampPosPOST24);
for i = 1:reps-1
    [maxAnglePOST24(i),timeMaxAnglePOST24(i)] =
    max(pos_listPOST24(timeStampPosPOST24(i):timeStampPosPOST24(i)+200));
    timeMaxAnglePOST24(i) =
    timeMaxAnglePOST24(i)+timeStampPosPOST24(i)-2;
end
endValuePOST24 = min([timeStampPosPOST24(reps)+250 tsspanPOST24(end)./10]);
[maxAnglePOST24(reps), timeMaxAnglePOST24(reps)] = 
max(pos_listPOST24(timeStampPosPOST24(reps):endValuePOST24));
timeMaxAnglePOST24(reps) =
timeMaxAnglePOST24(reps) + timeStampPosPOST24(reps) - 2;

%A plot of torque vs time and position vs time for all three tests is plotted.
figure(4)
plot(tspan, torque_list, tspan, pos_list, tspanPOST, torque_listPOST, tspanPOST, pos_listPOST, tspanPOST24, torque_listPOST24, tspanPOST24, pos_listPOST24)
xlabel('Time (ms)')
ylabel('Torque (Ft-lbs) and Anatomical Position (deg)')
title('Raw Biodex Data - s01')
legend(['Torque - Pre', 'Position - Pre', 'Torque - Post', 'Position - Post', 'Torque - Post24', 'Position - Post24', 'Location', 'SouthEast'])
grid on

%%
%This section plots each repetition overlapped on top of each other. An
%average repetition curve is plotted in black, for torque and for position,
%for each trial. Torque versus position is also plotted, using the average
%values.
numReps = length(timeStampPos);
if numReps == 5
  ERT imeList.t1 =
  [tspan(timeStampPos(1)+1):10:tspan(timeMaxAngle(1)+1)];
  ERT imeList.t2 =
  [tspan(timeStampPos(2)+1):10:tspan(timeMaxAngle(2)+1)];
  ERT imeList.t3 =
  [tspan(timeStampPos(3)+1):10:tspan(timeMaxAngle(3)+1)];
  ERT imeList.t4 =
  [tspan(timeStampPos(4)+1):10:tspan(timeMaxAngle(4)+1)];
  ERT imeList.t5 =
  [tspan(timeStampPos(5)+1):10:tspan(timeMaxAngle(5)+1)];
  numTimePoints = [length(ERT imeList.t1) length(ERT imeList.t2) length(ERT imeList.t3) length(ERT imeList.t4) length(ERT imeList.t5)];
  ERMaxTimePoints = min(numTimePoints);
  ERTorqueList.t1 = [torque_list((ERT imeList.t1+10)/10)];
  ERTorqueList.t2 = [torque_list((ERT imeList.t2+10)/10)];
  ERTorqueList.t3 = [torque_list((ERT imeList.t3+10)/10)];
  ERTorqueList.t4 = [torque_list((ERT imeList.t4+10)/10)];
  ERTorqueList.t5 = [torque_list((ERT imeList.t5+10)/10)];
  ERTorqueList.Average = zeros(1,ERMaxTimePoints);
  for i = 1:ERMaxTimePoints
    ERTorqueList.Average(i) = mean([ERTorqueList.t1(i) ERTorqueList.t2(i) ERTorqueList.t3(i) ERTorqueList.t4(i) ERTorqueList.t5(i)]);
  end
  ERO posList.t1 = [pos_list((ERT imeList.t1+10)/10)];
ERPosList.t2 = [pos_list((ERTimeList.t2+10)/10)];
ERPosList.t3 = [pos_list((ERTimeList.t3+10)/10)];
ERPosList.t4 = [pos_list((ERTimeList.t4+10)/10)];
ERPosList.t5 = [pos_list((ERTimeList.t5+10)/10)];
ERPosList.Average = zeros(1,ERMaxTimePoints);
for i = 1:ERMaxTimePoints
    ERPosList.Average(i) = mean([ERPosList.t1(i) ERPosList.t2(i) ERPosList.t3(i) ERPosList.t4(i) ERPosList.t5(i)]);
end
figure(5)
subplot(3,1,1)
plot(ERTimeList.t1-ERTimeList.t1(1), ERTorqueList.t1,ERTimeList.t2-ERTimeList.t2(1), ERTorqueList.t2,ERTimeList.t3-ERTimeList.t3(1), ERTorqueList.t3,ERTimeList.t4-ERTimeList.t4(1), ERTorqueList.t4,ERTimeList.t5-ERTimeList.t5(1), ERTorqueList.t5)
hold on
plot(ERTimeList.Average,ERTorqueList.Average,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Torque (Ft-lbs)')
title('Pre Pitching')
grid on
figure(6)
subplot(3,1,1)
plot(ERTimeList.t1-ERTimeList.t1(1), ERPosList.t1,ERTimeList.t2-ERTimeList.t2(1), ERPosList.t2,ERTimeList.t3-ERTimeList.t3(1), ERPosList.t3,ERTimeList.t4-ERTimeList.t4(1), ERPosList.t4,ERTimeList.t5-ERTimeList.t5(1), ERPosList.t5)
hold on
plot(ERTimeList.Average,ERPosList.Average,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Anatomical Position (deg)')
title('Pre Pitching')
grid on
elseif numReps == 4
    ERTimeList.t1 = [tspan(timeStampPos(1)+1):10:tspan(timeMaxAngle(1)+1)];
    ERTimeList.t2 = [tspan(timeStampPos(2)+1):10:tspan(timeMaxAngle(2)+1)];
    ERTimeList.t3 = [tspan(timeStampPos(3)+1):10:tspan(timeMaxAngle(3)+1)];
    ERTimeList.t4 = [tspan(timeStampPos(4)+1):10:tspan(timeMaxAngle(4)+1)];
    numTimePoints = [length(ERTimeList.t1) length(ERTimeList.t2) length(ERTimeList.t3) length(ERTimeList.t4) ];
    ERMaxTimePoints = min(numTimePoints);
    ERTorqueList.Average = [0:10:ERMaxTimePoints*10-10];
    ERTorqueList.t1 = [torque_list((ERTimeList.t1+10)/10)];
    ERTorqueList.t2 = [torque_list((ERTimeList.t2+10)/10)];
    ERTorqueList.t3 = [torque_list((ERTimeList.t3+10)/10)];
    ERTorqueList.t4 = [torque_list((ERTimeList.t4+10)/10)];
    ERTorqueList.Average = zeros(1,ERMaxTimePoints);
    for i = 1:ERMaxTimePoints
        ERTorqueList.Average(i) = mean([ERTorqueList.t1(i) ERTorqueList.t2(i) ERTorqueList.t3(i) ERTorqueList.t4(i)]);
end
ERPosList.t1 = [pos_list((ERTimeList.t1+10)/10)];
ERPosList.t2 = [pos_list((ERTimeList.t2+10)/10)];
ERPosList.t3 = [pos_list((ERTimeList.t3+10)/10)];
ERPosList.t4 = [pos_list((ERTimeList.t4+10)/10)];
ERTorqueList.t1 = \[torque\(\text{list}\((\text{ERTimeList.t1+10})/10)\)];
ERTorqueList.t2 = \[torque\(\text{list}\((\text{ERTimeList.t2+10})/10)\)];
ERTorqueList.t3 = \[torque\(\text{list}\((\text{ERTimeList.t3+10})/10)\)];
ERTorqueList.t4 = \[torque\(\text{list}\((\text{ERTimeList.t4+10})/10)\)];
for \(i = 1:\text{ERMaxTimePoints}\)
    ERPosList.Average(i) = mean([ERPosList.t1(i) ERPosList.t2(i) ERPosList.t3(i) ERPosList.t4(i)]);
end

figure(5)
subplot(3,1,1)
plot(ERTimeList.t1-ERTimeList.t1(1), ERTorqueList.t1, ERTimeList.t2-ERTimeList.t2(1), ERTorqueList.t2, ERTimeList.t3-ERTimeList.t3(1), ERTorqueList.t3, ERTimeList.t4-ERTimeList.t4(1), ERTorqueList.t4)
hold on
plot(ERTimeList.Average, ERTorqueList.Average, 'k', 'LineWidth', 2)
xlabel('Time (ms)')
ylabel('Torque (Ft-lbs)')
title('Pre Pitching')
grid on

figure(6)
subplot(3,1,1)
plot(ERTimeList.t1-ERTimeList.t1(1), ERPosList.t1, ERTimeList.t2-ERTimeList.t2(1), ERPosList.t2, ERTimeList.t3-ERTimeList.t3(1), ERPosList.t3, ERTimeList.t4-ERTimeList.t4(1), ERPosList.t4)
hold on
plot(ERTimeList.Average, ERPosList.Average, 'k', 'LineWidth', 2)
xlabel('Time (ms)')
ylabel('Anatomical Position (deg)')
title('Pre Pitching')
grid on

elseif numReps == 3

ERTimeList.t1 = [tspan(timeStampPos(1)+1):10:tspan(timeMaxAngle(1)+1)];
ERTimeList.t2 = [tspan(timeStampPos(2)+1):10:tspan(timeMaxAngle(2)+1)];
ERTimeList.t3 = [tspan(timeStampPos(3)+1):10:tspan(timeMaxAngle(3)+1)];
umTimePoints = [length(ERTimeList.t1) length(ERTimeList.t2) length(ERTimeList.t3)];
ERMaxTimePoints = min(numTimePoints);
ERTorqueList.t1 = [torque_list((ERTimeList.t1+10)/10)];
ERTorqueList.t2 = [torque_list((ERTimeList.t2+10)/10)];
ERTorqueList.t3 = [torque_list((ERTimeList.t3+10)/10)];
ERTorqueList.Average = zeros(1,ERMaxTimePoints);
for \(i = 1:\text{ERMaxTimePoints}\)
    ERTorqueList.Average(i) = mean([ERTorqueList.t1(i) ERTorqueList.t2(i) ERTorqueList.t3(i)]);
end
ERPosList.t1 = [pos_list((ERTimeList.t1+10)/10)];
ERPosList.t2 = [pos_list((ERTimeList.t2+10)/10)];
ERPosList.t3 = [pos_list((ERTimeList.t3+10)/10)];
ERPosList.Average = zeros(1,ERMaxTimePoints);
for i = 1:ERMaxTimePoints
    ERPosList.Average(i) = mean([ERPosList.t1(i) ERPosList.t2(i)
    ERPosList.t3(i)]);
end
figure(5)
subplot(3,1,1)
plot(ERTimeList.t1-ERTimeList.t1(1), ERTorqueList.t1,
    ERTimeList.t2-ERTimeList.t2(1), ERTorqueList.t2,
    ERTimeList.t3-ERTimeList.t3(1),
    ERTorqueList.t3)
hold on
plot(ERTimeList.Average,ERTorqueList.Average,'k', 'LineWidth',2)
xlabel('Time (ms)')
ylabel('Torque (Ft-lbs)')
title('Pre Pitching')
grid on
figure(6)
subplot(3,1,1)
plot(ERTimeList.t1-ERTimeList.t1(1), ERPosList.t1,
    ERTimeList.t2-ERTimeList.t2(1), ERPosList.t2,
    ERTimeList.t3-ERTimeList.t3(1),
    ERPosList.t3)
hold on
plot(ERTimeList.Average,ERPosList.Average,'k', 'LineWidth',2)
xlabel('Time (ms)')
ylabel('Anatomical Position (deg)')
title('Pre Pitching')
grid on
end
numReps = length(timeStampPosPOST);
if numReps == 5
    ERTimeList.t1POST = [tspanPOST(timeStampPosPOST(1)+1):10:tspanPOST(timeMaxAnglePOST(1)+1)];
    ERTimeList.t2POST = [tspanPOST(timeStampPosPOST(2)+1):10:tspanPOST(timeMaxAnglePOST(2)+1)];
    ERTimeList.t3POST = [tspanPOST(timeStampPosPOST(3)+1):10:tspanPOST(timeMaxAnglePOST(3)+1)];
    ERTimeList.t4POST = [tspanPOST(timeStampPosPOST(4)+1):10:tspanPOST(timeMaxAnglePOST(4)+1)];
    ERTimeList.t5POST = [tspanPOST(timeStampPosPOST(5)+1):10:tspanPOST(timeMaxAnglePOST(5)+1)];
    numTimePointsPOST = [length(ERTimeList.t1POST)
    length(ERTimeList.t2POST) length(ERTimeList.t3POST)
    length(ERTimeList.t4POST) length(ERTimeList.t5POST)];
    ERMaxTimePointsPOST = min(numTimePointsPOST);
end
numReps = length(timeStampPosPOST);
if numReps == 5
    ERTorqueList.t1POST = [torque_listPOST((ERTimeList.t1POST+10)/10)];
    ERTorqueList.t2POST = [torque_listPOST((ERTimeList.t2POST+10)/10)];
    ERTorqueList.t3POST = [torque_listPOST((ERTimeList.t3POST+10)/10)];
    ERTorqueList.t4POST = [torque_listPOST((ERTimeList.t4POST+10)/10)];
    ERTorqueList.t5POST = [torque_listPOST((ERTimeList.t5POST+10)/10)];
    ERTorqueList.AveragePOST = zeros(1,ERMaxTimePointsPOST);
end
for i = 1:ERMaxTimePointsPOST
ERTorqueList.AveragePOST(i) = mean([ERTorqueList.t1POST(i) ERTorqueList.t2POST(i) ERTorqueList.t3POST(i) ERTorqueList.t4POST(i) ERTorqueList.t5POST(i)]);  
end  
ERPosList.t1POST = [pos_listPOST((ERTimeList.t1POST+10)/10)];  
ERPosList.t2POST = [pos_listPOST((ERTimeList.t2POST+10)/10)];  
ERPosList.t3POST = [pos_listPOST((ERTimeList.t3POST+10)/10)];  
ERPosList.t4POST = [pos_listPOST((ERTimeList.t4POST+10)/10)];  
ERPosList.t5POST = [pos_listPOST((ERTimeList.t5POST+10)/10)];  
ERPosList.AveragePOST = zeros(1,ERMaxTimePointsPOST);  
for i = 1:ERMaxTimePointsPOST  
    ERPosList.AveragePOST(i) = mean([ERPosList.t1POST(i) ERPosList.t2POST(i) ERPosList.t3POST(i) ERPosList.t4POST(i) ERPosList.t5POST(i)]);  
end  
figure(5)  
subplot(3,1,2)  
plot(ERTimeList.t1POST-ERTimeList.t1POST(1), ERTorqueList.t1POST, ERTimeList.t2POST-ERTimeList.t2POST(1), ERTorqueList.t2POST, ERTimeList.t3POST-ERTimeList.t3POST(1), ERTorqueList.t3POST, ERTimeList.t4POST-ERTimeList.t4POST(1), ERTorqueList.t4POST, ERTimeList.t5POST-ERTimeList.t5POST(1), ERTorqueList.t5POST)  
hold on  
plot(ERTimeList.AveragePOST, ERTorqueList.AveragePOST, 'k', 'LineWidth', 2)  
xlabel('Time (ms)')  
ylabel('Torque (Ft-lbs)')  
title('Post Pitching')  
grid on  
figure(6)  
subplot(3,1,2)  
plot(ERTimeList.t1POST-ERTimeList.t1POST(1), ERPosList.t1POST, ERTimeList.t2POST-ERTimeList.t2POST(1), ERPosList.t2POST, ERTimeList.t3POST-ERTimeList.t3POST(1), ERPosList.t3POST, ERTimeList.t4POST-ERTimeList.t4POST(1), ERPosList.t4POST, ERTimeList.t5POST-ERTimeList.t5POST(1), ERPosList.t5POST)  
hold on  
plot(ERTimeList.AveragePOST, ERPosList.AveragePOST, 'k', 'LineWidth', 2)  
xlabel('Time (ms)')  
ylabel('Anatomical Position (deg)')  
title('Post Pitching')  
grid on  
elseif numReps == 4  
ERTimeList.t1POST = [tspanPOST(timeStampPosPOST(1)+1):10:tspanPOST(timeMaxAnglePOST(1)+1)];  
ERTimeList.t2POST = [tspanPOST(timeStampPosPOST(2)+1):10:tspanPOST(timeMaxAnglePOST(2)+1)];  
ERTimeList.t3POST = [tspanPOST(timeStampPosPOST(3)+1):10:tspanPOST(timeMaxAnglePOST(3)+1)];  
ERTimeList.t4POST = [tspanPOST(timeStampPosPOST(4)+1):10:tspanPOST(timeMaxAnglePOST(4)+1)];
numTimePointsPOST = [length(ERTimeList.t1POST) length(ERTimeList.t2POST) length(ERTimeList.t3POST) length(ERTimeList.t4POST)];
ERMaxTimePointsPOST = min(numTimePointsPOST);
ERTorqueList.AveragePOST = [0:10:ERMaxTimePointsPOST*10-10];
ERTorqueList.t1POST = [torque_listPOST((ERTimeList.t1POST+10)/10)];
ERTorqueList.t2POST = [torque_listPOST((ERTimeList.t2POST+10)/10)];
ERTorqueList.t3POST = [torque_listPOST((ERTimeList.t3POST+10)/10)];
ERTorqueList.t4POST = [torque_listPOST((ERTimeList.t4POST+10)/10)];
ERTorqueList.AveragePOST = zeros(1,ERMaxTimePointsPOST);
for i = 1:ERMaxTimePointsPOST
    ERTorqueList.AveragePOST(i) = mean([ERTorqueList.t1POST(i) ERTorqueList.t2POST(i) ERTorqueList.t3POST(i) ERTorqueList.t4POST(i)]);
end
ERPosList.t1POST = [pos_listPOST((ERTimeList.t1POST+10)/10)];
ERPosList.t2POST = [pos_listPOST((ERTimeList.t2POST+10)/10)];
ERPosList.t3POST = [pos_listPOST((ERTimeList.t3POST+10)/10)];
ERPosList.t4POST = [pos_listPOST((ERTimeList.t4POST+10)/10)];
ERPosList.AveragePOST = zeros(1,ERMaxTimePointsPOST);
for i = 1:ERMaxTimePointsPOST
    ERPosList.AveragePOST(i) = mean([ERPosList.t1POST(i) ERPosList.t2POST(i) ERPosList.t3POST(i) ERPosList.t4POST(i)]);
end
figure(5)
subplot(3,1,2)
plot(ERTimeList.t1POST-ERTimeList.t1POST(1), ERTorqueList.t1POST, ERTimeList.t2POST-ERTimeList.t2POST(1), ERTorqueList.t2POST, ERTimeList.t3POST-ERTimeList.t3POST(1), ERTorqueList.t3POST, ERTimeList.t4POST-ERTimeList.t4POST(1), ERTorqueList.t4POST)
hold on
plot(ERTimeList.AveragePOST, ERTorqueList.AveragePOST,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Torque (Ft-lbs)')
title('Post Pitching')
grid on
figure(6)
subplot(3,1,2)
plot(ERTimeList.t1POST-ERTimeList.t1POST(1), ERPosList.t1POST, ERTimeList.t2POST-ERTimeList.t2POST(1), ERPosList.t2POST, ERTimeList.t3POST-ERTimeList.t3POST(1), ERPosList.t3POST, ERTimeList.t4POST-ERTimeList.t4POST(1), ERPosList.t4POST)
hold on
plot(ERTimeList.AveragePOST, ERPosList.AveragePOST,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Anatomical Position (deg)')
title('Post Pitching')
grid on
else
    ERTimeList.t1POST = [tspanPOST(timeStampPosPOST(1)+1):10:tspanPOST(timeMaxAnglePOST(1)+1)];
end
ERTimeList.t2POST = [tspanPOST(timeStampPosPOST(2)+1):10:tspanPOST(timeMaxAnglePOST(2)+1)];
ERTimeList.t3POST = [tspanPOST(timeStampPosPOST(3)+1):10:tspanPOST(timeMaxAnglePOST(3)+1)];
numTimePointsPOST = [length(ERTimeList.t1POST) length(ERTimeList.t2POST) length(ERTimeList.t3POST)];
ERMaxTimePointsPOST = min(numTimePointsPOST);
ERTimeList.AveragePOST = [0:10:ERMaxTimePointsPOST*10-10];
ERTorqueList.t1POST = [torque_listPOST((ERTimeList.t1POST+10)/10)];
ERTorqueList.t2POST = [torque_listPOST((ERTimeList.t2POST+10)/10)];
ERTorqueList.t3POST = [torque_listPOST((ERTimeList.t3POST+10)/10)];
ERTorqueList.AveragePOST = zeros(1,ERMaxTimePointsPOST);
for i = 1:ERMaxTimePointsPOST
  ERTorqueList.AveragePOST(i) = mean([ERTorqueList.t1POST(i)
  ERTorqueList.t2POST(i) ERTorqueList.t3POST(i)]);
end
ERPosList.t1POST = [pos_listPOST((ERTimeList.t1POST+10)/10)];
ERPosList.t2POST = [pos_listPOST((ERTimeList.t2POST+10)/10)];
ERPosList.t3POST = [pos_listPOST((ERTimeList.t3POST+10)/10)];
ERPosList.AveragePOST = zeros(1,ERMaxTimePointsPOST);
for i = 1:ERMaxTimePointsPOST
  ERPosList.AveragePOST(i) = mean([ERPosList.t1POST(i)
  ERPosList.t2POST(i) ERPosList.t3POST(i)]);
end
figure(5)
subplot(3,1,2)
plot(ERTimeList.t1POST-ERTimeList.t1POST(1),
ERTorqueList.t1POST,ERTimeList.t2POST-ERTimeList.t2POST(1),
ERTorqueList.t2POST,ERTimeList.t3POST-ERTimeList.t3POST(1),
ERTorqueList.t3POST)
hold on
plot(ERTimeList.AveragePOST,ERTorqueList.AveragePOST,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Torque (Ft-lbs)')
title('Post Pitching')
grid on
figure(6)
subplot(3,1,2)
plot(ERTimeList.t1POST-ERTimeList.t1POST(1),
ERPosList.t1POST,ERTimeList.t2POST-ERTimeList.t2POST(1),
ERPosList.t2POST,ERTimeList.t3POST-ERTimeList.t3POST(1),
ERPosList.t3POST)
hold on
plot(ERTimeList.AveragePOST,ERPosList.AveragePOST,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Anatomical Position (deg)')
title('Post Pitching')
grid on
end
numReps = length(timeStampPosPOST24);
if numReps == 5
ERTimeList.t1POST24 = [tspanPOST24(timeStampPosPOST24(1)+1):10:tspanPOST24(timeMaxAnglePOST24 (1)+1)];
ERTimeList.t2POST24 = [tspanPOST24(timeStampPosPOST24(2)+1):10:tspanPOST24(timeMaxAnglePOST24 (2)+1)];
ERTimeList.t3POST24 = [tspanPOST24(timeStampPosPOST24(3)+1):10:tspanPOST24(timeMaxAnglePOST24 (3)+1)];
ERTimeList.t4POST24 = [tspanPOST24(timeStampPosPOST24(4)+1):10:tspanPOST24(timeMaxAnglePOST24 (4)+1)];
ERTimeList.t5POST24 = [tspanPOST24(timeStampPosPOST24(5)+1):10:tspanPOST24(timeMaxAnglePOST24 (5)+1)];
numTimePointsPOST24 = [length(ERTimeList.t1POST24) length(ERTimeList.t2POST24) length(ERTimeList.t4POST24) length(ERTimeList.t5POST24)];
ERMaxTimePointsPOST24 = min(numTimePointsPOST24);
ERTimeList.AveragePOST24 = [0:10:ERMaxTimePointsPOST24*10-10];
ERTorqueList.t1POST24 = [torque_listPOST24((ERTimeList.t1POST24+10)/10)];
ERTorqueList.t2POST24 = [torque_listPOST24((ERTimeList.t2POST24+10)/10)];
ERTorqueList.t3POST24 = [torque_listPOST24((ERTimeList.t3POST24+10)/10)];
ERTorqueList.t4POST24 = [torque_listPOST24((ERTimeList.t4POST24+10)/10)];
ERTorqueList.t5POST24 = [torque_listPOST24((ERTimeList.t5POST24+10)/10)];
ERTorqueList.AveragePOST24 = zeros(1,ERMaxTimePointsPOST24);
for i = 1:ERMaxTimePointsPOST24
    ERTorqueList.AveragePOST24(i) = mean([ERTorqueList.t1POST24(i) ERTorqueList.t2POST24(i) ERTorqueList.t3POST24(i) ERTorqueList.t4POST24(i) ERTorqueList.t5POST24(i)]);
end
ERPosList.t1POST24 = [pos_listPOST24((ERTimeList.t1POST24+10)/10)];
ERPosList.t2POST24 = [pos_listPOST24((ERTimeList.t2POST24+10)/10)];
ERPosList.t3POST24 = [pos_listPOST24((ERTimeList.t3POST24+10)/10)];
ERPosList.t4POST24 = [pos_listPOST24((ERTimeList.t4POST24+10)/10)];
ERPosList.t5POST24 = [pos_listPOST24((ERTimeList.t5POST24+10)/10)];
ERPosList.AveragePOST24 = zeros(1,ERMaxTimePointsPOST24);
for i = 1:ERMaxTimePointsPOST24
    ERPosList.AveragePOST24(i) = mean([ERPosList.t1POST24(i) ERPosList.t2POST24(i) ERPosList.t3POST24(i) ERPosList.t4POST24(i) ERPosList.t5POST24(i)]);
end
figure(5)
subplot(3,1,3)
plot(ERTimeList.t1POST24-ERTimeList.t1POST24(1), ERTorqueList.t1POST24, ERTorqueList.t2POST24-ERTimeList.t2POST24(1), ERTorqueList.t3POST24, ERTorqueList.t4POST24-ERTimeList.t4POST24(1), ERTorqueList.t5POST24, ERTimeList.t4POST24-ERTimeList.t4POST24(1),

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ERTorqueList.t4POST24, ERTorqueList.t5POST24 = ERTorqueList.t5POST24(1),
hold on
plot(ERTorqueList.AveragePOST24, ERTorqueList.AveragePOST24, 'k', 'LineWidth', 2)
xlabel('Time (ms)')
ylabel('Torque (Ft-lbs)')
title('24 hrs Post Pitching')
grid on
figure(6)
subplot(3,1,3)
plot(ERTimeList.t1POST24 - ERTimeList.t1POST24(1),
ERPosList.t1POST24, ERTimeList.t2POST24 - ERTimeList.t2POST24(1),
ERPosList.t2POST24, ERTimeList.t3POST24 - ERTimeList.t3POST24(1),
ERPosList.t3POST24, ERTimeList.t4POST24 - ERTimeList.t4POST24(1),
ERPosList.t4POST24, ERTimeList.t5POST24 - ERTimeList.t5POST24(1),
ERPosList.t5POST24)
hold on
plot(ERTorqueList.AveragePOST24, ERPosList.AveragePOST24, 'k', 'LineWidth', 2)
xlabel('Time (ms)')
ylabel('Anatomical Position (deg)')
title('24 hrs Post Pitching')
grid on
elseif numReps == 4
ERTimeList.t1POST24 =
[tspanPOST24(timeStampPosPOST24(1)+1):10:tspanPOST24(timeMaxAnglePOST24 (1)+1)];
ERTimeList.t2POST24 =
[tspanPOST24(timeStampPosPOST24(2)+1):10:tspanPOST24(timeMaxAnglePOST24 (2)+1)];
ERTimeList.t3POST24 =
[tspanPOST24(timeStampPosPOST24(3)+1):10:tspanPOST24(timeMaxAnglePOST24 (3)+1)];
ERTimeList.t4POST24 =
[tspanPOST24(timeStampPosPOST24(4)+1):10:tspanPOST24(timeMaxAnglePOST24 (4)+1)];
numTimePointsPOST24 = [length(ERTimeList.t1POST24)
length(ERTimeList.t2POST24) length(ERTimeList.t3POST24)
length(ERTimeList.t4POST24)];
ERTimeList.AveragePOST24 = [0:10:ERMaxTimePointsPOST24*10-10];
ERTorqueList.t1POST24 =
[torque_listPOST24((ERTimeList.t1POST24+10)/10)];
ERTorqueList.t2POST24 =
[torque_listPOST24((ERTimeList.t2POST24+10)/10)];
ERTorqueList.t3POST24 =
[torque_listPOST24((ERTimeList.t3POST24+10)/10)];
ERTorqueList.t4POST24 =
[torque_listPOST24((ERTimeList.t4POST24+10)/10)];
ERTorqueList.AveragePOST24 = zeros(1,ERMaxTimePointsPOST24);
for i = 1:ERMaxTimePointsPOST24
ERTorqueList.AveragePOST24(i) = mean([ERTorqueList.t1POST24(i)
ERTorqueList.t2POST24(i) ERTorqueList.t3POST24(i)
ERTorqueList.t4POST24(i)]);
end

ERPosList.t1POST24 = [pos_listPOST24((ERTimeList.t1POST24+10)/10)];
ERPosList.t2POST24 = [pos_listPOST24((ERTimeList.t2POST24+10)/10)];
ERPosList.t3POST24 = [pos_listPOST24((ERTimeList.t3POST24+10)/10)];
ERPosList.t4POST24 = [pos_listPOST24((ERTimeList.t4POST24+10)/10)];
ERPosList.AveragePOST24 = zeros(1,ERMaxTimePointsPOST24);
for i = 1:ERMaxTimePointsPOST24
  ERPosList.AveragePOST24(i) = mean([ERPosList.t1POST24(i)
  ERPosList.t2POST24(i) ERPosList.t3POST24(i) ERPosList.t4POST24(i)]);
end

figure(5)
subplot(3,1,3)
plot(ERTimeList.t1POST24-ERTimeList.t1POST24(1),
ERTorqueList.t1POST24,ERTimeList.t2POST24-ERTimeList.t2POST24(1),
ERTorqueList.t2POST24,ERTTimeList.t3POST24-ERTimeList.t3POST24(1),
ERTorqueList.t3POST24,ERTTimeList.t4POST24-ERTimeList.t4POST24(1),
ERTorqueList.t4POST24)
hold on
plot(ERTimeList.AveragePOST24,ERTorqueList.AveragePOST24,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Torque (Ft-lbs)')
grid on
figure(6)
subplot(3,1,3)
plot(ERTimeList.t1POST24-ERTimeList.t1POST24(1),
ERPosList.t1POST24,ERTimeList.t2POST24-ERTimeList.t2POST24(1),
ERPosList.t2POST24,ERTimeList.t3POST24-ERTimeList.t3POST24(1),
ERPosList.t3POST24,ERTimeList.t4POST24-ERTimeList.t4POST24(1),
ERPosList.t4POST24)
hold on
plot(ERTimeList.AveragePOST24,ERPosList.AveragePOST24,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Anatomical Position (deg)')
grid on
else
ERTimeList.t1POST24 =
[tspanPOST24(timeStampPosPOST24(1)+1):10:tspanPOST24(timeMaxAnglePOST24
(1)+1)];
ERTimeList.t2POST24 =
[tspanPOST24(timeStampPosPOST24(2)+1):10:tspanPOST24(timeMaxAnglePOST24
(2)+1)];
ERTimeList.t3POST24 =
[tspanPOST24(timeStampPosPOST24(3)+1):10:tspanPOST24(timeMaxAnglePOST24
(3)+1)];
numTimePointsPOST24 = [length(ERTimeList.t1POST24)
length(ERTimeList.t2POST24) length(ERTimeList.t3POST24)];
ERTMaxTimePointsPOST24 = min(numTimePointsPOST24);
ERTorqueList.AveragePOST24 = [0:10:ERTMaxTimePointsPOST24*10-10];
ERTorqueList.t1POST24 =
[torque_listPOST24((ERTimeList.t1POST24+10)/10)];
ERTorqueList.t2POST24 =
[torque_listPOST24((ERTimeList.t2POST24+10)/10)];
ERTorqueList.t3POST24 =
[torque_listPOST24((ERTimeList.t3POST24+10)/10)];
ERTorqueList.AveragePOST24 = zeros(1,ERTMaxTimePointsPOST24);
for i = 1:ERTMaxTimePointsPOST24
ERTorqueList.AveragePOST24(i) = mean([ERTorqueList.t1POST24(i)
ERTorqueList.t2POST24(i) ERTorqueList.t3POST24(i)]);
end
ERPosList.t1POST24 = [pos_listPOST24((ERTimeList.t1POST24+10)/10)];
ERPosList.t2POST24 = [pos_listPOST24((ERTimeList.t2POST24+10)/10)];
ERPosList.t3POST24 = [pos_listPOST24((ERTimeList.t3POST24+10)/10)];
ERPosList.AveragePOST24 = zeros(1,ERTMaxTimePointsPOST24);
for i = 1:ERTMaxTimePointsPOST24
ERPosList.AveragePOST24(i) = mean([ERPosList.t1POST24(i)
ERPosList.t2POST24(i) ERPosList.t3POST24(i)]);
end
figure(5)
subplot(3,1,3)
plot(ERTimeList.t1POST24-
ERTimeList.t1POST24(1),
ERTorqueList.t1POST24,ERTimeList.t2POST24-
ERTimeList.t2POST24(1),
ERTorqueList.t2POST24,ERTimeList.t3POST24-
ERTimeList.t3POST24(1),
ERTorqueList.t3POST24)
hold on
plot(ERTimeList.AveragePOST24,ERTorqueList.AveragePOST24,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Torque (Ft-lbs)')
title('24 hrs Post Pitching')
grid on
figure(6)
subplot(3,1,3)
plot(ERTimeList.t1POST24-ERTimeList.t1POST24(1),
ERPosList.t1POST24,ERTimeList.t2POST24-ERTimeList.t2POST24(1),
ERPosList.t2POST24,ERTimeList.t3POST24-ERTimeList.t3POST24(1),
ERPosList.t3POST24)
hold on
plot(ERTimeList.AveragePOST24,ERPosList.AveragePOST24,'k','LineWidth',2)
xlabel('Time (ms)')
ylabel('Anatomical Position (deg)')
title('24 hrs Post Pitching')
grid on
end
figure(7)
plot(ERPosList.Average,ERTorqueList.Average,ERPosList.AveragePOST,ERTorqueList.AveragePOST,ERPosList.AveragePOST24,ERTorqueList.AveragePOST24)
xlabel('Anatomical Position (deg)')
ylabel('Torque (Ft-lbs)')
title('Torque vs Position')
legend('Pre','Post','24 hrs Post','Location','SouthEast')
grid on

%The torque vs. position curves of each trial (pre, post, and post24) were
%normalized to the same starting angle. The averages of each trial were
%plotted. A linear polynomial fit line was added to each trial over the
%first 10 degrees. The slopes of these lines are the stiffness values.
%Values were saved to an Excel file.
figure(8)
ERPosList.AveragePOSTshift = ERPosList.AveragePOST -
(min(ERPosList.AveragePOST)-min(ERPosList.Average));
ERPosList.AveragePOST24shift = ERPosList.AveragePOST24 -
(min(ERPosList.AveragePOST24)-min(ERPosList.Average));
plot(ERPosList.Average,ERTorqueList.Average,ERPosList.AveragePOSTshift,
ERTorqueList.Average,ERPosList.AveragePOST24shift,ERTorqueList.AveragePOST24)
xlabel('Anatomical Position (deg)')
ylabel('Torque (Ft-lbs)')
title('Torque vs Position')
legend('Pre','Post','24 hrs Post','Location','SouthEast')
grid on

angleTofind = 10;
torTofind = 10;
startAngle =
[min(ERPosList.Average);min(ERPosList.AveragePOSTshift);min(ERPosList.AveragePOST24shift)]
angleFind = find(ERPosList.Average >= (angleTofind+startAngle(1)));
angleFindPOST = find(ERPosList.AveragePOSTshift >=
(angleTofind+startAngle(2)));
angleFindPOST24 = find(ERPosList.AveragePOST24shift >=
(angleTofind+startAngle(3)));
hold on
if ~isempty(angleFind)
    p =
polyfit(ERPosList.Average(1:(angleFind(1))),ERTorqueList.Average(1:angleFind(1)),1);
torplot = p(1)*ERPosList.Average(1:angleFind(1))+p(2);
    plot(ERPosList.Average(1:angleFind(1)),torplot,'--b')
else
    disp('Error - Angle requirement not met for PRE')
p(1) = 0;
end
if ~isempty(angleFindPOST)
pPOST =
polyfit(ERPosList.AveragePOSTshift(1:(angleFindPOST(1))),ERTorqueList.AveragePOST(1:angleFindPOST(1)),1);
torplotPOST = pPOST(1)*ERPosList.AveragePOSTshift(1:(angleFindPOST(1))) + pPOST(2);

plot(ERPosList.AveragePOSTshift(1:(angleFindPOST(1))),torplotPOST,'--g')
else
disp('Error - Angle requirement not met for POST')
pPOST(1) = 0;
end
if ~isempty(angleFindPOST24)
pPOST24 = polyfit(ERPosList.AveragePOST24shift(1:(angleFindPOST24(1))),ERTorqueList.AveragePOST24(1:angleFindPOST24(1)),1);
torplotPOST24 = pPOST24(1)*ERPosList.AveragePOST24shift(1:angleFindPOST24(1)) + pPOST24(2);
plot(ERPosList.AveragePOST24shift(1:(angleFindPOST24(1))),torplotPOST24,'--r')
else
disp('Error - Angle requirement not met for POST24')
pPOST24(1) = 0;
end
Stiffness = [p(1); pPOST(1); pPOST24(1)]
StiffnessFileName = 'Stiffness_Data';
StiffnessSheet = [subjID '_rate'];
xlswrite(StiffnessFileName,Stiffness,StiffnessSheet)

%%
%Peak torque values were found, as well as where they occured. Values were
%saved to an Excel file.
figure(9)
plot(ERPosList.Average,ERTorqueList.Average,ERPosList.AveragePOSTshift,ERTorqueList.AveragePOST,ERPosList.AveragePOST24shift,ERTorqueList.AveragePOST24)
xlabel('Anatomical Position (deg)')
ylabel('Torque (Ft-lbs)')
title('Torque vs Position')
legend(['Pre','Post','24 hrs Post','Location','SouthEast'])
grid on
[maxT, iPos] = max(ERTorqueList.Average);
[maxTPOST, iPOST] = max(ERTorqueList.AveragePOST);
[maxTPOST24, iPOST24] = max(ERTorqueList.AveragePOST24);
maxpos = ERPosList.Average(iPos);
maxposPOST = ERPosList.AveragePOSTshift(iPOST);
maxposPOST24 = ERPosList.AveragePOST24shift(iPOST24);
hold on
plot(maxpos,maxT,'bo',maxposPOST,maxTPOST,'go',maxposPOST24,maxTPOST24,'ro')
peakpos_achieved = [maxpos; maxposPOST; maxposPOST24] -
[min(ERPosList.Average); min(ERPosList.AveragePOSTshift); min(ERPosList.AveragePOST24shift)];
maxTproduced = [maxT; maxTPOST; maxTPOST24];
PeakTorqueData = [peakpos_achieved, maxTproduced];
FileName = 'PeakTorqueAngle_Data';
Sheet = [subjID ' ' rate];
xlswrite(FileName, PeakTorqueData, Sheet)

% Values were then plotted on the previous figure, and the figure was saved
to a .bmp file.
figure(8)
hold on
plot(maxpos, maxT, 'bo', maxposPOST, maxTPOST, 'go', maxposPOST24, maxTPOST24, 'ro')
legend('Pre', 'Post', '24 hrs Post', 'Stiffness - Pre', 'Stiffness - Post', 'Stiffness - 24 hrs Post', 'Maximum Torque - Pre', 'Maximum Torque - Post', 'Maximum Torque - 24 hrs Post', 'Location', 'SouthWest')
torqueplotname = [subjID ' ' rate];
print('-dbmp', torqueplotname)
Appendix B: Borg Scale

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>NOTHING AT ALL</td>
</tr>
<tr>
<td>0.5</td>
<td>VERY, VERY LIGHT</td>
</tr>
<tr>
<td>1</td>
<td>VERY LIGHT</td>
</tr>
<tr>
<td>2</td>
<td>FAIRLY LIGHT</td>
</tr>
<tr>
<td>3</td>
<td>MODERATE</td>
</tr>
<tr>
<td>4</td>
<td>SOMewhat HARD</td>
</tr>
<tr>
<td>5</td>
<td>HARD</td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>VERY HARD</td>
</tr>
<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>VERY VERY HARD (MAXIMAL)</td>
</tr>
</tbody>
</table>