IMPLICATIONS OF PLANAR POSTURAL METRICS AND KINEMATICS ON PITCH VELOCITY AND KINETICS IN BASEBALL PITCHERS

By

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ABSTRACT OF THE DISSERTATION

Implications of Planar Postural Metrics and Kinematics on Pitch Velocity and Kinetics in Baseball Pitchers

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Dissertation Director: William Craelius, Ph.D.

Two key metrics to a baseball pitcher’s success and longevity are their pitch velocity and injury risk. Pitchers are susceptible to injury due to high velocities and stresses generated during the pitching motion. These injuries commonly occur at the shoulder or elbow and are typically a result of high torques experienced at the segment joint. Some pitchers reduce their joint torque by having a more efficient pitching motion in which their mechanics allow for a high pitch velocity and decreased torque. As a result, it is important to determine metrics that decrease torque, while maintaining pitch velocity. There is a need to expand the knowledge of these postural and kinematic metrics, and to analyze anatomical factors that may influence them.

The mechanics of 62 pitchers were examined through motion capture, and an array of metrics in all three anatomical planes was analyzed for correlations to pitch velocity and maximum torque in the form of elbow varus torque, shoulder internal rotation torque, and shoulder horizontal abduction torque. The correlated metrics included kinematic angular velocities and postural metrics at three pitching checkpoints of foot plant, maximum external rotation (MER), and release. In terms of postural metrics knee flexion at MER (r = -0.453) and shoulder external rotation at MER (r = 0.465) both
had moderate correlations to pitch velocity, but no implications for injury. Alternatively, pelvis forward tilt, trunk forward tilt, and shoulder horizontal abduction were determined to be tradeoff metrics in which an increase in angle resulted in both an increase in pitch velocity and torque. These postural metrics had the highest correlations to torque but were only weak correlations. Kinematic parameters had moderate to strong correlations for both pitch velocity and torque. There was no crossover between the correlated metrics with pitch velocity having correlations to the maximum angular velocities of the sagittal pelvis, transverse torso, sagittal elbow, and transverse shoulder horizontal adduction. All three examined torques had correlations to the maximum hand angular velocity in each of the three planes of motion. The highest correlation was maximum hand sagittal angular velocity to maximum elbow varus torque ($r = 0.745$).

Anatomical factors of height, weight, age, segment lengths, arm slot, and mobility were examined for their influence on the postural and kinematic metrics. Weight was correlated to pitch velocity and height to arm slot. In terms of arm slot, it was discovered that pitchers with a more vertical arm slot use more sagittal plane movements to gain velocity, while more horizontal arm slot pitchers use transverse plane movements. Mobility assessments provided significant differences between pitchers with limited mobility and pitchers with adequate mobility. The pitchers with limited mobility had more significant decreases in metrics correlated to pitch velocity and increases in upper extremity kinetics. It is important for pitchers to maintain their mobility to combat anatomical adaptations, maintain pitch velocity, and mitigate their risk of injury. Pitching coaches can use this information to develop better individualized training programs to help pitchers improve performance while decreasing their risk of injury.
DEDICATION

This document is dedicated to my parents, family, and friends for their support, patience, and inspiration.
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# Table of Contents

Abstract.....................................................................................................................II

Table of Contents..................................................................................................V

Table of Figures....................................................................................................XI

Table of Tables......................................................................................................XIV

Table of Equations.................................................................................................XVI

Chapter 1: Introduction..........................................................................................1
  1.1 Study Introduction and Aims...........................................................................1
  1.2 Background......................................................................................................3
  1.3 Introduction to Motion Capture......................................................................5

Chapter 2: Methods.................................................................................................7
  2.1 System............................................................................................................7
  2.2 Data Collection..............................................................................................8
  2.3 Data Processing............................................................................................10
  2.4 Generated Metrics.......................................................................................11
    2.4.1 Metrics...................................................................................................11
    2.4.2 Rotation angles and tilts.......................................................................12
  2.5 Checkpoints .................................................................................................12
  2.6 Subject Exclusion.........................................................................................14
  2.7 Subject Demographics................................................................................14
  2.8 Studies and Trial Numbers...........................................................................14

Part 1: Postural metric and kinematic correlations to velocity and torque.........15

Chapter 3: Study 1 – Velocity Correlations and Averages.................................16
3.1 Background ............................................................................................. 16
3.2 Methods ................................................................................................. 17
3.3 Results ................................................................................................... 20
3.4 Discussion ............................................................................................. 24
  3.4.1 Planar Kinematics ............................................................................. 24
    3.4.1.1 Kinematic Sequence Metrics .................................................. 24
    3.4.1.2 Planar Kinematic MLR ......................................................... 25
    3.4.1.3 Sagittal Plane Kinematics ..................................................... 26
    3.4.1.4 Frontal Plane Kinematics .................................................... 26
    3.4.1.5 Transverse Plane Kinematics .............................................. 27
  3.4.2 Postural Metrics .............................................................................. 27
    3.4.2.1 Highest Correlated Metrics .................................................. 27
    3.4.2.2 Pelvic Forward Tilt .............................................................. 28
    3.4.2.3 Shoulder External Rotation .............................................. 29
    3.4.2.4 Lead Knee Flexion .............................................................. 29
    3.4.2.5 Trunk Forward Tilt .............................................................. 30
    3.4.2.6 Postural Grouping MLR ..................................................... 31
  3.5 Limitations and Future Direction ....................................................... 31
  3.6 Conclusion .......................................................................................... 32

Chapter 4: Study 2 – Torque Correlations and Averages .................. 32
  4.1 Background ....................................................................................... 32
  4.2 Methods .............................................................................................. 35
    4.2.1 Torque Normalization ............................................................. 35
4.2.2 Statistical Analysis……………………………………………………35
4.3 Results……………………………………………………………………36
   4.3.1 Averages………………………………………………………………36
   4.3.2 Maximum Elbow Varus Torque Before Release…………………39
   4.3.3 Maximum Shoulder Internal Rotation Torque Before Release……41
   4.3.4 Maximum Shoulder Horizontal Abduction Torque Before Release.44
4.4 Discussion…………………………………………………………………46
   4.4.1 Averages………………………………………………………………46
   4.4.2 Maximum Elbow Varus Torque Before Release…………………..47
      4.4.2.1 Kinematics…………………………………………………47
      4.4.2.2 Postural Metrics…………………………………………47
   4.4.3 Maximum Shoulder Internal Rotation Torque Before Release……48
      4.4.3.1 Kinematics…………………………………………………48
      4.4.3.2 Postural Metrics…………………………………………49
   4.4.4 Maximum Shoulder Horizontal Abduction Torque Before Release.49
      4.4.4.1 Kinematics…………………………………………………49
      4.4.4.2 Postural Metrics…………………………………………50
   4.4.5 Postural Grouping MLR……………………………………………50
4.5 Limitations and Future Direction………………………………………..51
4.6 Conclusion …………………………………………………………………51
Part 1: Summary ……………………………………………………………..51
Part 2: Factors that influence postural metrics and kinematics……………54
Chapter 5: Study 3 – Differences attributed to height, weight, age, and segment length.54
5.1 Background........................................................................................................54

5.2 Methods.............................................................................................................55
   5.2.1 Segment Lengths.........................................................................................55
   5.2.2 Statistical Analysis......................................................................................56

5.3 Results...............................................................................................................57

5.4 Discussion.........................................................................................................61
   5.4.1 Height..........................................................................................................61
   5.4.2 Weight.........................................................................................................61
   5.4.3 Age.............................................................................................................62
   5.4.4 Interactions between Height, Weight, and Age........................................63
   5.4.5 Segment Length..........................................................................................63

5.5 Limitation and Future Direction.......................................................................64

5.6 Conclusion........................................................................................................64

Chapter 6: Study 4 – Differences attributed to arm slot.........................................65

6.1 Background.......................................................................................................65

6.2 Methods.............................................................................................................67
   6.2.1 Calculating Arm Slot.................................................................................67
   6.2.2 Arm Slot Groups.........................................................................................69
   6.2.3 Statistical Analysis.......................................................................................70

6.3 Results...............................................................................................................71
   6.3.1 ANOVA Results.........................................................................................71
   6.3.2 Correlations to Ball Velocity......................................................................76
   6.3.3 Kinematic Multiple Linear Regression.......................................................78
Appendix 2.3 Comparison Heatmaps of Pitch Velocity and Torque Correlations…

..............................................................................................................................................123
# Table of Figures

Figure 1: Pitching temporal parameters and phases ........................................ 4  
Figure 2: Kinematic sequence graph ............................................................ 7  
Figure 3: Mocap coordinate system ............................................................. 8  
Figure 4: Mocap calibrations ................................................................. 9  
Figure 5: Visual 3D skeleton ................................................................. 10  
Figure 6: Rotational angle direction ......................................................... 12  
Figure 7: Pitching checkpoints ............................................................... 13  
Figure 8: Planar kinematic correlations to velocity .................................... 21  
Figure 9: Transverse plane kinematic correlations to velocity ..................... 22  
Figure 10: Postural metric correlations to velocity ..................................... 23  
Figure 11: Planar postural metric correlations to velocity ............................. 24  
Figure 12: Torque normalization ............................................................ 35  
Figure 13: Average torque values before release ....................................... 37  
Figure 14: Average torque values after release ......................................... 38  
Figure 15: Planar kinematic correlations to maximum elbow varus torque ....... 39  
Figure 16: Transverse plane kinematic correlations to maximum elbow varus torque .... 39  
Figure 17: Postural metric correlations to maximum elbow varus torque ........ 40  
Figure 18: Planar postural metric correlations to maximum elbow varus torque ............. 41  
Figure 19: Planar kinematic correlations to maximum shoulder internal rotation torque . . 41  
Figure 20: Transverse plane kinematic correlations to maximum shoulder internal rotation torque ................................................................. 42
Figure 21: Postural metric correlations to maximum shoulder internal rotation torque………………………………………………………………………………...42
Figure 22: Planar postural metric correlations to maximum shoulder internal rotation torque………………………………………………………………………………...43
Figure 23: Planar kinematic correlations to maximum shoulder horizontal abduction torque…………………………………………………………………………………….44
Figure 24: Transverse plane kinematic correlations to maximum shoulder horizontal abduction torque…………………………………………………………………………………….44
Figure 25: Postural metric correlations to maximum shoulder horizontal abduction torque…………………………………………………………………………………….45
Figure 26: Planar postural metric correlations to maximum shoulder horizontal abduction torque…………………………………………………………………………………….46
Figure 27: Height correlations……………………………………………………………………………………………………………………………………………………………………57
Figure 28: Weight correlations……………………………………………………………………………………………………………………………………………………………………58
Figure 29: Age correlations……………………………………………………………………………………………………………………………………………………………………58
Figure 30: Height, weight, and age interactions……………………………………………………………………………………………………………………………………………………………………59
Figure 31: Trunk length correlations……………………………………………………………………………………………………………………………………………………………………60
Figure 32: Arm slot angle………………………………………………………………………………………………………………………………………………………………………………………65
Figure 33: Segment length equations……………………………………………………………………………………………………………………………………………………………………67
Figure 34: Arm angle geometric equations……………………………………………………………………………………………………………………………………………………………………68
Figure 35: Arm slot angle calculation……………………………………………………………………………………………………………………………………………………………………68
Figure 36: Arm slot ranges………………………………………………………………………………………………………………………………………………………………………………………69
Figure 37: Arm slot velocity correlations to planar postural metrics……………………………………………………………………………………………………………………………………………………………………79
Figure 38: Sample size equations.................................................................94
**Table of Tables**

Table 1: Subject Demographics.................................................................14
Table 2: Identification of number of trials representing each pitcher in each study........15
Table 3: Angular velocities utilized for planar kinematics correlation....................16
Table 4: Postural metrics for MLR................................................................19
Table 5: Postural metric averages at all three checkpoints........................................20
Table 6: Maximum planar kinematic averages.......................................................21
Table 7: Means and standard deviations of included torque values.........................36
Table 8: Postural Metric Groupings based on Velocity and Torque Correlations.......52
Table 9: Kinematic Metric Groupings based on Velocity and Torque Correlations......53
Table 10: Arm Slot ANOVA Kinematics.............................................................71
Table 11: Arm Slot ANOVA Pelvis.................................................................72
Table 12: Arm Slot ANOVA Trunk Metrics.........................................................73
Table 13: Arm Slot ANOVA Lead Knee Metrics..................................................74
Table 14: Arm Slot ANOVA Arm Metrics..........................................................74
Table 15: Arm Slot ANOVA Hip-Shoulder Separation Metrics...............................75
Table 16: Overhand pitchers five highest correlations to ball velocity.....................76
Table 17: Three-quarter pitchers five highest correlations to ball velocity..............77
Table 18: Sidearm pitchers five highest correlations to ball velocity.......................78
Table 19: Included Mobility Assessments.........................................................94
Table 20: Tight Neck Flexor Potential Implications..............................................95
Table 21: Insufficient Serratus Strength Potential Implications.............................96
Table 22: Tight Pec Minor Potential Implications...............................................97
Table 23: Tight Lats Potential Implications.................................................................98
Table 24: Insufficient T-spine Extension Potential Implications...............................100
Table 25: Tight Adductors Potential Implications.......................................................101
Table of Equations

Equation 1: Torque normalization equation...............................................................35
Equation 2: Length of the upper arm equation.........................................................67
Equation 3: Length of the forearm equation............................................................67
Equation 4: Arm hypotenuse length equation.........................................................68
Equation 5: Angle of the arm with respect to the wrist equation..............................68
Equation 6: Arm slot angle equation.................................................................68
Equation 7: Sample size equation with z-score ......................................................94
Equation 8: Sample size equation with t-score......................................................94
Chapter 1: Introduction

1.1 Study Introduction and Aims

Pitch velocity and injury risk are two of the main factors that influence a pitcher’s success and recruitment potential in the game of baseball [1]. Pitch velocity is directly related to how quickly the baseball reaches home plate after it is released from the pitcher’s hand. Increasing pitch velocity decreases the time the ball takes to reach home plate, which gives the batter less time to react. In Major League Baseball (MLB), high pitch velocity is associated with pitcher success, which makes it a prime target for pitcher development [2].

Unfortunately, pitch velocity has been found to be correlated to elbow varus torque, with increasing torque resulting in an increase in the risk of injury [3]. As such, the push for pitchers to increase their fastball velocity could be one of the factors contributing to the recent increase in pitcher upper extremity injuries [4,5]. Due to the stress created from the anatomical positioning and kinematics involved in throwing a baseball, pitchers are consistently above the failure threshold of the ulnar collateral ligament (UCL) of the elbow [6]. Repetitively putting the UCL under high stress can lead to injury in the form of a UCL tear, which requires surgery and over a year of recovery and rehabilitation. The severity and frequency of pitcher shoulder and elbow injuries has led to an increase in research centered around joint torques. Research into joint torques has discovered that not all pitchers exhibit a positive correlation between torque and pitch velocity, and that older pitchers may be able to attenuate some of their torque through either physical maturity or better pitching mechanics [7]. This raises awareness of
mechanical efficiency in pitching, and adjustments pitchers can make within their mechanics to maintain pitch velocity while decreasing torque.

Current research into pitch velocity and torque is typically focused on specific postural metrics and kinematics, where kinematics is defined as the angular velocities of anatomical segments, which leaves a gap in the metrics examined and resulting knowledge. We look to close this gap in two ways. First, we will examine the relationship between pitch velocity, torque, and planar biomechanics. Planar biomechanics are the movement of the body in each plane of motion. We will be examining the movement of all major anatomical segments in each plane in terms of postural metrics (joint angles), kinematics, and kinetics. The results of these correlation studies will present additional information on which metrics contribute to pitch velocity and torque during the pitching motion, and the significance of movement in each plane of motion. Having this information allows coaches and trainers to tailor pitching programs through adjustments in movement patterns to optimize pitch velocity, while decreasing torque.

Second, we will further examine factors that may influence postural metrics and kinematics. Currently, research leaves out anatomical factors such as height, segment length, arm slot, and mobility that may affect or limit postural metrics and kinematics. Determining influential factors elucidates information on why a pitcher is exhibiting certain metrics and movement patterns which can be used to inform training strategies. The aim of these studies is to provide coaches and practitioners with insight into the connections between a pitcher’s anatomy and their pitch velocity and torque to create a more individualized approach to training. This information could additionally be applied to other sports or exercises that use similar movements.
1.2 Background

Baseball pitching is a complex motion that involves intricately sequencing multiple body segments in multiple planes at high speeds. A pitcher could choose a variety of different motions to organize their body to achieve the goal of throwing a baseball. These motions can be limited by factors such as pitcher mobility and the rules of baseball. Also, not all motions are optimal for the goals of velocity, movement, accuracy, and health. As a result, coaches and researchers have set out to compare different pitching motions to determine the optimal mechanics for pitcher success.

To allow for comparison of pitching mechanics between pitchers the pitching motion has been broken down in the literature into six phases and five temporal parameters [8,9]. The five temporal parameters are used as checkpoints to ensure pitchers achieve specific positions within their pitching motion, as shown in Figure 1. The five temporal parameters are leg lift, foot plant, maximum (max) external rotation, release, and max internal rotation. Leg lift is the point in the delivery where the pitcher’s lead knee reaches its maximum height and occurs at the beginning of the pitching motion. The next temporal parameter sequentially is foot plant. Foot plant is the only temporal parameter that does not have a set definition and varies from researcher to researcher. Throughout this study, foot plant is defined as the moment when the whole lead foot of the pitcher first contacts the ground. Other definitions of foot plant include first touch of the foot on the ground, and weight bearing foot plant where the foot experiences a certain percentage of body weight. Max external rotation is a temporal parameter and a postural pitching metric. The postural metric is the maximum pitching shoulder external rotation, and the temporal parameter is the time point at which this maximum angle occurs. Release is the
point the ball leaves the hand of the pitcher and is followed by max internal rotation. Max internal rotation is the moment the pitcher achieves their maximum pitching shoulder internal rotation angle.

![Figure 1: The phases (bottom text), and temporal parameters (top text) of the pitching motion.](image)

As shown in **Figure 1**, the five temporal parameters occur at the transition point between the six phases. The six phases are the wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow-through. The wind-up phase is the initiation of the pitching motion where the pitcher begins gaining momentum down the mound. The wind-up phase starts at first move and ends at leg lift. The wind-up is also the most individual, rhythmic, and stylized part of the pitching motion. Here the pitcher adopts a repeatable motion that is comfortable for them. Many pitchers approach the wind-up differently some coming to a static balance point and others moving their center of mass towards home plate. The wind-up us additionally influenced by the presence or absence of runners on base: in an attempt to hold baserunners, pitchers will generally simplify their wind-up to make their motion quicker to home plate.

The stride phase is where the body generates most of its momentum in preparation for sending energy up the kinetic chain at foot plant. The stride phase begins at leg lift and
continues until foot plant. The arm cocking phase follows the stride phase and is when the body gets into proper positioning for maximal external rotation (MER). After MER, the arm begins internal rotation accelerating forward during the acceleration phase. During this phase is when kinetic energy accumulated in previous phases is transferred to the ball at release. The deceleration phase is important for arm health as it is the phase where the arm slows down and dissipates any energy not transferred to the ball. Finally, once the shoulder reaches max internal rotation the pitcher enters the follow-through phase of the pitching motion. During this phase, all movements from the previous phases stop, allowing a pitcher to come to a balance point [10]. These phases and checkpoints are used in the literature and in practice as a map of the pitching motion.

1.3 Introduction to Motion Capture

The current gold standard in baseball pitching biomechanical data collection is marker-based optical motion capture (mocap). Mocap tracks small reflective spheres or markers that are placed at specific anatomical landmarks on the body to recreate a person’s skeletal anatomy. Mocap systems use multiple cameras each at a different angle to capture the position of the reflective markers throughout the pitching motion. From the positioning of the cameras, the computer software determines the locations of the markers in three dimensions [11]. The resulting locations are then automatically input into software that assigns a player’s skeletal position based on anatomical marker identification. Finally, the skeleton is used to generate joint angles, angular velocities, center of gravity, and kinetic variables of forces and torques for analysis.

The data output from motion capture is typically viewed in three ways, static metrics, kinematic sequence graphs, and angular graphs. Static metrics are checkpoints
used to examine a pitcher’s positioning at key points in the pitching motion. These static metrics are typically viewed in a table of means and are used to compare pitching metrics and run statistical analysis. The second way that mocap data is used is in a kinematic sequence plot, which consists of the angular velocities of different segments throughout the duration of the pitch (Figure 2). These plots typically display four of the major anatomical segments of the pelvis, torso, shoulder, and then either the elbow or the hand. The pelvis, torso, and shoulder are all represented by their transverse angular velocity, while the hand and elbow are represented by their sagittal angular velocity. These anatomical planes are chosen as they are believed to have the highest contribution to pitch velocity for each segment and are used to depict the transfer of energy up the kinetic chain in a proximal to distal progression [12]. These graphs are analyzed in terms of their sequence and maximum values. To maintain a proximal to distal progression, a pitcher must sequence their segments in the order of pelvis, torso, shoulder, and hand [13]. The magnitude of each curve shows the maximal velocity of that segment and has a direct relationship to the energy generated. This graph represents part of a pitcher’s kinematics, which are important to understand in terms of pitcher performance and injury. The final application of the motion capture data is in angular graphs, which are not utilized in this study. Angular graphs are simply a graph of a specific joint angle over time and shows how the angle changes throughout the pitching motion.
Chapter 2: Methods

2.1 System

A 10 camera Qualisys Miqus optical motion capture system was used to collect all the pitching data in this study. The system is permanently stationed around a pitching mound in a baseball training facility, where it performed marker-based mocap. Trials were collected at a sampling rate of 300Hz through the use reflective markers with a diameter of 19mm. The Qualisys PAF Baseball MAC Marker set was used for marker placement, which consisted of 41 markers placed at prescribed anatomical locations on the pitcher and 7 markers placed on the mound (Appendix 2.1). The lab coordinate system origin was the bottom right corner of the pitching rubber, and the coordinate system was defined as the x-axis extending from the rubber towards home plate, the y-axis running along the face of the mound, perpendicular to the x-axis, and the z-axis

\textbf{Figure 2}: Kinematic sequence graph representing the angular velocities of the pelvis (red), torso (green), shoulder (blue), and hand (black). The vertical black lines are foot plant and release, respectively.
coming out of the face of the rubber vertically (Figure 3). The x-axis thus created the sagittal plane, the y-axis the frontal plane, and the z-axis the transverse plane.

2.2 Data Collection

In preparation for data collection the pitchers were told to warm-up following their normal routine. During this time the mocap system was calibrated, and the mound markers were put in place. When the pitcher was ready, we began marker placement on their body. This process consisted of spraying the pitcher with adhesive spray over 34 of the marker locations, and then placing the markers on their subsequent location. The markers for the head were placed on a hat, and the feet markers were taped onto the
pitcher’s shoes. During marker placement the pitcher was also instructed of the mocap process and what was expected of them. Pitchers also provided information such as their height, weight, birth date, and injury history. Once all the markers were placed on the body then the pitcher would stand on the rubber for two calibrations, a static calibration, and a functional knee calibration. The static calibration involved the subject standing in what is referred to as a ski pole position (see Figure 4), while the functional knee calibration involved the subject in the same position, while performing continuous half squats.

**Figure 4:** Mocap calibration stances and marker placement. Static calibration (1), and functional knee calibration (2-4). For the static position the subject stands with knees slightly bent, elbows out and bent to about 90° as if holding ski poles, and looking straight ahead. For the functional knee calibration, the subject starts in the same position (2), squats to about 60° of knee flexion (3), and then returns to the starting position (4). This process (steps 2-4) is repeated for a total of 30 seconds.

After calibration the pitcher was instructed to throw some additional warm up pitches to get used to the feel of pitching with the markers on. Once the pitcher was
ready, they were instructed to throw 10 fastballs at 100% exertion. The velocity of each pitch was recorded using a PocketRadar Ball Coach radar gun. After each pitch the pitcher would get a 30 second break to better simulate a real game and reduce any effects of fatigue. If part of the pitching motion fell outside the 5-second capture window, or a marker was lost during the pitch than this capture would be labeled as a mistrial and an additional pitch would be thrown to take its place. This was used in an attempt to get 10 usable captures per pitcher. Other factors that affected the number of usable pitches were the health of the pitcher (how many pitches they could throw), not recognizing missing markers, and poor marker tracking.

### 2.3 Data Processing

Four pitches from each pitcher were randomly selected to use in data processing. Four was chosen as it was the minimum usable pitch number displayed across all subjects meaning that every pitcher in this study had four or more usable captures to process. Once the four pitches were randomly chosen from their sample size using a Python random number generator these pitches were processed. To process the data each capture was checked to ensure that the model was complete with all markers identified and all gaps filled. Gap filling was done through the use of interpolation (linear, polynomial, or relational) to ensure that each marker was seen throughout the entire duration of the pitch. The data
was also smoothed in the Qualisys Track Manager (QTM) to remove any unwanted noise, and the foot plant event was created. Foot plant was identified as the moment the entire foot contacted the ground and was checked by ensuring that this happened when the ankle began to decelerate or pass through zero depending on the landing technique. The ankle deceleration trend was found using the angular velocity graph of the ankle markers. This data was then sent to Visual 3D (Figure 5). Qualisys has their own Visual 3D baseball module that takes the QTM and converts it into a skeleton, while also generating all the anatomical, kinematic, and kinetic data for each pitch. This data includes metrics such as joint angles, joint moments, and angular velocities. These metrics were then exported from Visual 3D as a text file, de-identified and used for data analysis.

2.4 Generated metrics

2.4.1 Metrics

The Qualisys Visual 3D module generates the angles for each joint, the torque for the elbow and shoulder, the center of mass, and angular velocities of various segments all in the sagittal, frontal, and transverse plane. These metrics are all calculated for the duration of the pitch. A complete list of metrics, their corresponding descriptions, and sign conventions can be found in Appendix 2.2.

2.4.2 Rotational angles and tilt

Pelvis and trunk rotational angles follow the convention in Figure 6. For a right-handed pitcher facing home plate is $0^\circ$, facing third base is $90^\circ$, and facing second base is
180°. Rotating counterclockwise past home plate becomes a negative rotation angle. A left-handed pitcher follows the opposite convention as they are rotating clockwise during the pitch so facing home plate is 0°, facing first base is 90°, and facing second base is 180°.

There are two types of tilts referenced throughout this study: forward tilt and lateral tilt. A forward tilt is characterized as a positive angle, and a backwards tilt as a negative angle. A positive lateral tilt is tilt toward the glove side. For a right-handed pitcher a positive lateral tilt would then be a tilt toward the left, and for a left-handed pitcher would be a tilt toward the right.

**Figure 6:** Pelvis and trunk rotational angles for a right-handed pitcher. The arrows are going in the direction of rotation during the pitching motion.

### 2.5 Checkpoints

Since the metrics output by mocap are continuous for the duration of the pitching motion it is very difficult to directly compare them not only to each other, but also to
velocity and torque. To clarify the situation, three checkpoints were determined during the pitching motion to use for metric comparisons. These three checkpoints are foot plant, maximum external rotation, and release (Figure 7). These checkpoints are three of the five temporal parameters determined for the pitching motion. These parameters are utilized to determine if a pitcher is in a good position or falls within a specified range of data at each checkpoint within the pitching motion and to correlate postural metrics to velocity and torque values [14]. As discussed in the introduction foot plant is defined as the moment the whole foot of the pitcher contacts the ground, max external rotation is the moment the pitcher hits their maximum shoulder external rotation angle, and release is the moment the pitcher lets go of the baseball. Throughout this study postural metrics will be examined with reference to these checkpoints. For example, trunk forward tilt at foot plant is the angle of trunk forward tilt that the pitcher had at the moment their whole foot contacted the ground. Elbow flexion at max external rotation is the angle of elbow flexion when the pitcher achieved their maximum amount of shoulder external rotation. Kinematic and kinetic metrics are analyzed with reference to their maximum magnitude.

<table>
<thead>
<tr>
<th>Foot Plant</th>
<th>Max External Rotation</th>
<th>Release</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Foot Plant" /></td>
<td><img src="image2" alt="Max External Rotation" /></td>
<td><img src="image3" alt="Release" /></td>
</tr>
</tbody>
</table>

**Figure 7:** Skeletal positioning of a pitcher at each of the three checkpoints utilized throughout this study.
2.6 Subject exclusion

Subjects were excluded from this study if they did not have four usable recorded pitches. Pitches were marked as unusable if they had gaps, were missing markers, no pitch velocity was recorded, or the marker tracking by the cameras was inadequate as seen by visually noticeable marker drift or constant flickering.

2.7 Subject demographics and pitch velocity

This study used data from 62 baseball pitchers. All the pitchers were male, and their demographics can be seen in Table 1. The pitchers ranged in age from 15 years old to 29 years old with an average age of 19 years old. The mean weight and height of these pitchers were 190.4lbs and 71.7in, respectively. Of the 62 pitchers, 42 pitchers threw with their right hand and 20 pitchers threw with their left hand. There was a wide range of pitch velocities with the slowest pitch recorded at 59mph and the fastest at 90mph. The mean pitch velocity was 80.1mph with a standard deviation of 6.5mph.

<table>
<thead>
<tr>
<th>Demographic</th>
<th>Range</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>15-29</td>
<td>19.0</td>
<td>3.3</td>
<td>years</td>
</tr>
<tr>
<td>Weight</td>
<td>147-244</td>
<td>190.4</td>
<td>22.7</td>
<td>lbs</td>
</tr>
<tr>
<td>Height</td>
<td>60-78</td>
<td>71.7</td>
<td>3.2</td>
<td>inches</td>
</tr>
<tr>
<td>Pitch Velocity</td>
<td>59-90</td>
<td>80.1</td>
<td>6.5</td>
<td>mph</td>
</tr>
</tbody>
</table>

2.8 Studies and Trial Numbers

Overall, five studies were conducted to analyze the effect of baseball pitching planar biomechanics on pitcher injury and pitch velocity. Two studies examined the direct relationship through postural metric and kinematic correlations to velocity and
torque. The other three studies examined indirect relationships to pitch velocity and torque through factors that influence postural metrics and kinematics.

Depending on the data being analyzed in each study statistical analysis was performed using either the average data, or individual trials (Table 2). The first two studies used individual trials for running correlations, while the other three studies used averages for pitcher groupings. The average data is the mean of each metric found from the four pitching trials of each subject. For the average data each pitcher is only represented once, where for the individual trial analysis each pitcher is represented four times (once for each pitch analyzed).

<table>
<thead>
<tr>
<th>Study Number</th>
<th>Study Name</th>
<th>Type of Analysis</th>
<th>Number of Trials per pitcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Velocity Correlations</td>
<td>Individual Trials</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Torque Correlations</td>
<td>Individual Trials</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Height, Weight, Age, and Segment Length</td>
<td>Average</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Arm Slot</td>
<td>Average</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Mobility</td>
<td>Average</td>
<td>1</td>
</tr>
</tbody>
</table>

Part 1: Postural metric and kinematic correlations to velocity and torque

Here we examine relationships between planar biomechanics, pitch velocity, and torque values. It is thought that upper extremity metrics related to the shoulder, elbow, and hand would have higher correlations than lower extremity metrics to both pitch velocity and torque. When combined the results of this section can be grouped in one of four categories: individual, tradeoff, positive, or negative. An individual metric has a correlation to either pitch velocity or torque values, but not both. A tradeoff metric has the same correlation direction to both metrics, meaning that it will either increase or
decrease both pitch velocity and torques. Tradeoff metrics need to be further assessed to determine if the gain in velocity is worth the gain in torque. Positive metrics have an inverse relationship between torque and pitch velocity, meaning that they can increase velocity, while simultaneously decreasing torque. Positive metrics are the ones most beneficial to the efficiency of pitching mechanics. Negative metrics also have an inverse relationship between pitch velocity and torque, but they decrease pitch velocity while increasing torque values. Negative metrics are ones that would need to be carefully monitored and flagged by pitching coaches.

Chapter 3: Study 1 - Velocity Correlations and Averages

3.1 Background

Two of the biggest factors affecting a pitcher’s success are the velocity and break of their pitches. Having a high velocity fastball is a sought-after pitch to set up other pitch types and is a recognized attribute of an elite pitcher [1,15]. The higher the velocity of the pitch, the less time a batter must react, thus increasing the effectiveness of the pitch. In addition, maximizing pitch velocity was one of three metrics associated with MLB pitcher success [2]. As a result, pitchers and coaches seek metrics or knowledge that can be implemented into their training to lead to a higher velocity. This has been done previously through methodologies examining postural metrics, kinematics, and temporal parameters. Postural metrics are angles of the body at specific points in time such as trunk forward tilt at foot plant, which gives insight into which positions at specific checkpoints might be beneficial to gaining velocity. Two such postural metrics that are consistently correlated to pitch velocity are maximum shoulder external rotation and
trunk forward tilt [16-18]. Both these metrics increase the distance over which the arm travels, which in turn increases time to apply force to the ball and as such increasing these metrics increases pitch velocity [19].

Kinematics are how fast a particular segment moves in a plane of motion. Few kinematic variables have been observed in correspondence with pitch velocity, and the ones that have been examined are typically in the transverse plane with both the pelvis and torso rotation angular velocities being found to be correlated to pitch velocity [20]. In addition, temporal differences between kinematic variables have also been studied in relation to pitch velocity. The time difference between max torso rotation angular velocity and max pelvis angular velocity, and the time difference between max torso rotation angular velocity and max elbow extension angular velocity have each been found to be correlated to pitch velocity [21,22]. It is thought that shifts in the timing of kinematic parameters represent changes in momentum transfer, and that having a more efficient momentum transfer increases pitch velocity [23].

3.2 Methods

We expand upon the already established research by determining correlations to pitch velocity of both individual planar kinematics (Table 3) and postural metrics (Table 4). Correlations are conducted through the use of linear regression techniques.

Linear regression was performed using Pearson’s correlation coefficient (r). All postural metrics were examined at foot plant, max external rotation, and release. To improve the robustness of regression results, we remove any outliers through Cook’s distance. Cook’s distance determines the influence of a data point on the regression
model, which can then be removed if it surpasses a certain threshold. In this experiment the cutoff threshold was chosen as $4/n$, where $n$ is the sample size. Any data point that exceeds this cutoff threshold was then removed from the data set before performing the regression. In addition to outliers, any data pair that was not complete because one of the pairs was an NaN (Not a Number) was also removed from the analysis. An NaN occurs when a value is missing in the data.

Regression analysis was then performed to find the Pearson’s correlation coefficient and hypothesis significance of the correlation in terms of the probability value (p-value). The Pearson’s correlation coefficient signifies the relationship between two variables, with a coefficient greater than 0.4 signifying a moderate relationship [24]. Due to the large number of factors examined, typically only correlation coefficients of 0.4 or higher are mentioned in this study. Additionally key postural metrics are listed in the results section as they are used for the planar multiple linear regression (MLR). Multiple linear regression uses multiple dependent variables to fit an equation and predict the independent variable response, as compared to the Pearson’s correlation coefficient, which has one dependent and one independent variable. No postural metrics outside the key postural metrics were determined to have an r-value above 0.4, which is why they are not listed in the results section.

Planar kinematics used in linear regression were examined for all three planes using the five segments seen in the kinematic sequence, which are the pelvis, torso, shoulder, elbow, and hand. There is no shoulder kinematics in the sagittal plane, and two metrics for shoulder kinematics in the transverse plane. The metrics used for planar kinematics is the maximum angular velocity of each segment in each plane.
<table>
<thead>
<tr>
<th>Plane</th>
<th>Pelvis</th>
<th>Torso</th>
<th>Shoulder</th>
<th>Elbow</th>
<th>Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal</td>
<td>Forward Tilt</td>
<td>Forward Tilt</td>
<td>Extension</td>
<td>Flexion</td>
<td></td>
</tr>
<tr>
<td>Frontal</td>
<td>Lateral Tilt</td>
<td>Lateral Tilt</td>
<td>Abduction</td>
<td>Varus</td>
<td>Ulnar Deviation</td>
</tr>
<tr>
<td>Transverse</td>
<td>Rotation</td>
<td>Rotation</td>
<td>External Rotation and Horizontal Adduction</td>
<td>Pronation</td>
<td>Pronation</td>
</tr>
</tbody>
</table>

Multiple linear regression was also performed both on the planar kinematics and the postural metrics on pitch velocity with $\alpha = 0.05$ to determine the significance and correlation coefficient for each plane. For planar kinematics MLR was performed for each plane, with the transverse plane having two separate regressions one with shoulder external rotation angular velocity and one with shoulder horizontal adduction velocity. The postural metrics chosen to represent each plane can be found in Table 4. These key metrics were grouped by plane, and then used for MLR. MLR for postural plane correlations was also performed at the three checkpoints of foot plant, max external rotation, and release.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Pelvic Forward Tilt</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Trunk Forward Tilt</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Pelvic Rotation</td>
<td>Transverse</td>
</tr>
<tr>
<td>Trunk Rotation</td>
<td>Transverse</td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction</td>
<td>Transverse</td>
</tr>
<tr>
<td>Shoulder External Rotation</td>
<td>Transverse</td>
</tr>
<tr>
<td>Trunk Lateral Tilt</td>
<td>Frontal</td>
</tr>
<tr>
<td>Shoulder Abduction</td>
<td>Frontal</td>
</tr>
</tbody>
</table>
3.3 Results

<table>
<thead>
<tr>
<th>Metric</th>
<th>Foot Plant</th>
<th>Max External Rotation</th>
<th>Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion</td>
<td>41.13°</td>
<td>38.55°</td>
<td>31.76°</td>
</tr>
<tr>
<td>Pelvic Forward Tilt</td>
<td>11.92°</td>
<td>34.37°</td>
<td>38.07°</td>
</tr>
<tr>
<td>Trunk Forward Tilt</td>
<td>-3.275°</td>
<td>20.72°</td>
<td>31.95°</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td>93.37°</td>
<td>85.55°</td>
<td>21.38°</td>
</tr>
<tr>
<td>Pelvic Rotation</td>
<td>47.43°</td>
<td>-8.246°</td>
<td>-12.60°</td>
</tr>
<tr>
<td>Trunk Rotation</td>
<td>99.29°</td>
<td>13.11°</td>
<td>-2.220°</td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction</td>
<td>-13.65°</td>
<td>16.87°</td>
<td>9.673°</td>
</tr>
<tr>
<td>Shoulder External Rotation</td>
<td>46.10°</td>
<td>157.9°</td>
<td>100.2°</td>
</tr>
<tr>
<td>Trunk Lateral Tilt</td>
<td>8.565°</td>
<td>22.50°</td>
<td>27.66°</td>
</tr>
<tr>
<td>Shoulder Abduction</td>
<td>93.22°</td>
<td>95.36°</td>
<td>98.18°</td>
</tr>
</tbody>
</table>

The general trends observed for each metric are as follows: The reduction in knee flexion from foot plant to release signifies that the pitcher is extending their knee into release. Pelvic and trunk forward tilt increases as well demonstrating that the pitcher is in more of a pelvic anterior tilt as they bring their chest over their front foot. The elbow stays around 90° for foot plant and max external rotation helping to reduce stress on the elbow, after which it extends into release. The pelvis rotates ahead of the trunk as seen by their differences in rotation angle and is typically passed home plate by max external rotation. The trunk on the other hand follows the pelvis getting closer in degrees from foot plant to release but doesn’t pass 0° until release. Shoulder horizontal abduction starts in adduction, but then transitions into abduction as the arm comes forward into release. Shoulder external rotation starts low at foot plant and can get up to over 180° at its maximum. Once the shoulder reaches its maximum it then begins internal rotation into and after release. Trunk lateral tilt for most pitchers is toward their glove side leading to a higher arm slot. It can be seen in the data that the pitcher starts with minimal trunk tilt but
increases the tilt throughout the pitch until they reach the tilt that lines up with their arm slot at release. There are no ideal ranges for trunk lateral tilt at release as these are arm slot dependent. Shoulder abduction remains relatively constant throughout the pitch and should maintain an angle of about 90°.

**Table 6: Maximum planar kinematic averages**

<table>
<thead>
<tr>
<th>Plane</th>
<th>Pelvis</th>
<th>Torso</th>
<th>Shoulder</th>
<th>Elbow</th>
<th>Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal</td>
<td>295.4°/s</td>
<td>332.2°/s</td>
<td>NaN</td>
<td>2305°/s</td>
<td>4568°/s</td>
</tr>
<tr>
<td>Frontal</td>
<td>347.8°/s</td>
<td>281.3°/s</td>
<td>597.6°/s</td>
<td>1047°/s</td>
<td>2694°/s</td>
</tr>
<tr>
<td>Transverse</td>
<td>670.0°/s</td>
<td>1083°/s</td>
<td>4886°/s</td>
<td>1116°/s</td>
<td>5922°/s</td>
</tr>
</tbody>
</table>

Planar kinematic averages are the maximum angular velocities of each segment in each plane. There is a general trend of increasing maximum angular velocity from proximal to distal segments with a few exceptions. In each plane the hand has the fastest angular velocities reaching speeds upwards of 5000°/s.

**Figure 8:** Correlations for planar kinematics to pitch velocity. Each segment metric is the maximum angular velocity of that metric in the respective plane. There is no metric for the shoulder in the sagittal plane. The MLR column is the multiple linear regression combining the metrics for each segment in each plane.
The highest kinematic correlation ($r = 0.436$) to pitch velocity is the maximum pelvis sagittal plane angular velocity, which is how quickly the pelvis is anteriorly tilting during the pitching motion. The second highest correlation is also in the sagittal plane with maximum elbow extension velocity ($r = 0.423$). These two metrics aided the sagittal plane kinematics in having the highest planar correlation through multiple linear regression with a Pearson’s correlation coefficient of 0.179. The hand had the lowest correlations to pitch velocity not being able to exceed an $r$-value of 0.184 in any plane. The frontal plane also had two relatively high correlations of $r = 0.382$ and $r = 0.378$ for shoulder abduction angular velocity and pelvic lateral tilt angular velocity respectively. In the transverse plane only, the torso had a correlation coefficient above 0.27 with $r = 0.418$.

![Planar Kinematics Correlations to Velocity](image)

**Figure 9:** Correlations for planar kinematics to pitch velocity, where shoulder horizontal adduction velocity replaced shoulder external rotation velocity in the shoulder column.

Substituting max shoulder horizontal adduction velocity into the shoulder column of the transverse plane resulted in an $r$ of 0.410 and raised the MLR result to 0.172.
At foot plant the highest correlation to pitch velocity is shoulder horizontal abduction. Here shoulder horizontal abduction is represented by a negative number meaning that the more abduction a pitcher has at foot plant the higher their pitch velocity. It can also be seen that metrics begin to have a more significant impact at max external rotation, where four metrics have an absolute correlation greater than 0.4. These four metrics are knee flexion, pelvic forward tilt, trunk forward tilt, and shoulder external rotation. Shoulder external rotation and pelvic forward tilt both maintain their correlations through release, whereas both knee flexion and trunk forward tilt correlations
begin to decrease. Certain metrics including trunk lateral tilt, pelvic rotation, trunk rotation, and shoulder abduction have little postural correlations to pitch velocity.

![Planar Postural Metric Correlations to Velocity](image)

**Figure 11:** Multiple linear regression correlations of postural metrics grouped by plane to pitch velocity at the three checkpoints of foot plant, max external rotation, and release.

Grouping the postural metrics by plane did not provide much additional insight into which planes contribute to pitch velocity most and when. All three planes had low correlations under 0.27 at all three checkpoints, with the highest correlation being the sagittal plane at max external rotation with an r-value of 0.270. Through the postural metrics it can be seen that the frontal plane doesn’t contribute much to pitch velocity as it consistently has correlation coefficients around 0.

### 3.4 Discussion

#### 3.4.1 Planar Kinematics

**3.4.1.1 Kinematic Sequence Metrics**

Planar kinematics is assessing the influence of the max angular velocity of the five main pitching body segments in each plane on pitch velocity. Five of these metrics
are ones typically examined in the kinematic sequence [13]. These metrics are pelvis rotation angular velocity, torso rotation angular velocity, shoulder internal rotation angular velocity, elbow extension angular velocity, and hand flexion angular velocity. Of these five metrics only two have correlations to pitch velocity over 0.27. These metrics are the max torso rotation angular velocity with $r = 0.418$, and the max elbow extension angular velocity with $r = 0.423$. Both these metrics have previously been found to be significantly greater in high velocity pitchers as compared to lower velocity pitchers [25-27]. Rapid elbow extension before release is a result of the counterclockwise rotation of the torso meaning that the maximum trunk rotation velocity contributes energy to the elbow extension velocity and may explain why they both had high correlations [28]. The other metrics even though they are not as highly correlated to pitch velocity are important to drive energy transfer up the kinetic chain [29,30].

3.4.1.2 Planar Kinematic MLR

The MLR of the planar kinematics looked to determine if the kinematics of any singular plane was highly correlated to pitch velocity. The results of this test determined that when grouping the kinematics by plane no single plane alone was highly correlated to pitch velocity as each plane had a correlation coefficient under 0.18. This suggests that a pitcher cannot rely on their angular velocity in one plane and needs to be able to generate angular velocity in multiple planes and transfer this energy between planes.
3.4.1.3 Sagittal Plane Kinematics

Each plane had two kinematic metrics with a decent correlation to pitch velocity. In the sagittal plane these were pelvis forward tilt angular velocity and elbow extension angular velocity. Pelvic forward tilt angular velocity is how quickly the pitcher is anteriorly tilting their pelvis during the pitching motion. Pelvic anterior tilt allows for increased extension of the lumbar and thoracic spine thus facilitating shoulder external rotation. Thoracic extension increases scapular posterior tilting, external rotation, and maximum shoulder external rotation [31]. Max elbow extension angular velocity typically occurs right after max external rotation and is how quickly a pitcher is able to get from their roughly 90° flexed position at max external rotation to an extended position at release. The quicker a pitcher is able to extend their elbow the more their arm is being used as a whip to transfer energy into the ball.

3.4.1.4 Frontal Plane Kinematics

In the frontal plane the highest correlations to velocity were pelvic lateral tilt angular velocity and shoulder abduction angular velocity. Neither of these correlations reached the moderate correlation ranking of 0.4, but they do raise questions for future research. Typically, pelvic lateral tilt is not a movement that is discussed in pitching, and one would think would create instability within the system. This makes it interesting that laterally tilting the pelvis faster would lead to a higher pitch velocity. Shoulder abduction is a metric that most practitioners look to maintain a uniform angle of 90° throughout the pitching motion for stability and to decrease shoulder kinetics while increasing ball velocity [8,32,33]. Shoulder abduction does appear to remain relatively stable throughout
the duration of the pitch in Table 5 suggesting that these angular velocities may be achieved over a very small angular distance. Both these findings bring up the importance of the frontal plane in the pitching motion, and how these velocities contribute to pitch velocity. Further research is needed in this area to provide additional insight into the connections between these metrics and pitching mechanics.

3.4.1.5 Transverse Plane Kinematics

The transverse plane had torso rotation angular velocity \((r = 0.418)\) and shoulder horizontal adduction angular velocity \((r = 0.410)\) both be correlated to pitch velocity. Torso rotational angular velocity is the link between energy taken from the ground and energy transferred to the arm. Without efficient torso mechanics and energy generation through rapid torso rotation the arm will have limited energy causing limited pitch velocity. Shoulder horizontal adduction angular velocity is how fast a pitcher takes their arm from a loaded abduction position behind their torso to a position in line with or in front of their torso at release. The quicker a pitcher can do this the more force will be created to put the arm into a good external rotation position thus contributing to the shoulder external rotation correlation at max external rotation.

3.4.2 Postural Metrics

3.4.2.1 Highest Correlated Metrics

It was found that pelvic forward tilt has the highest correlation to throwing velocity both at MER and at release with Pearson’s correlation coefficient \((r)\) of 0.582 and 0.559 respectively. This means that there is a relationship between pelvic tilt and
throwing velocity, and since the relationship is positive this means that the more pelvic
tilt a pitcher has the higher their velocity (verified by p<0.05 for each metric). Other
metrics with a moderate correlation to throwing velocity in order of highest to lowest
correlation are shoulder external rotation at MER (r = 0.465), knee flexion at MER (r =
-0.453), and trunk forward tilt at MER (r = 0.401). For the positive correlations
increasing the angle of the metric is related to increasing pitching velocity and vice versa
for the negative correlation. It should be noted that due to the complexity of the pitching
motion, and the interactions between body parts that it is extremely difficult to find
strong correlations, which are correlation coefficients of 0.7 or higher.

3.4.2.2 Pelvic Forward Tilt

It was surprising to find that pelvic tilt had the highest correlation to throwing
velocity. This is due to the fact that it is an unconscious movement used to facilitate
movement of the upper body. Increasing pelvic tilt in the anterior direction allows for
both increased trunk forward tilt and max external rotation, which are both correlated to
velocity. As a result, pelvic tilt doesn’t have a direct connection to pitch velocity, but
instead increases pitch velocity through facilitating other important movements. Most of
the pitchers have about a 4° difference in pelvic tilt between MER and release. This small
difference explains why pelvic tilt at release is also correlated to pitch velocity. The
importance of the pelvic control has been examined in other studies that have found that
professional pitchers with better lumbopelvic control had fewer walks and hits per inning
pitched and missed less time due to injury [34-36].
### 3.4.2.3 Shoulder External Rotation

Shoulder external rotation at MER is just the maximum external rotation of the shoulder. The more you can increase max external rotation the more time and distance you will have to apply force to the ball [19]. In this respect you can think of your arm like a catapult the farther you pull back the catapult the farther and faster the item your throwing is going to travel. This means that the farther you can pull back your arm the faster the ball is going to leave your hand as your arm has more time to gather speed before release. This is why the average maximum external rotation is 157° pitchers are trying to get as much stretch and distance as possible for their arm to deliver the ball. The average external rotation at release was 100° so pitchers on average are giving themselves 57° of arc for the ball to travel over before release. This explains why maximum shoulder external rotation has been found to be correlated to pitch velocity [8].

### 3.4.2.4 Lead Knee Flexion

Here knee flexion is negatively correlated to pitch velocity, which means that we want the knee to be extending at the point of MER and can be seen with the roughly 10° decrease in knee flexion angle from foot plant to release. Knee extension of the lead leg is a metric that is correlated with pitch velocity [37]. It is also associated with stabilizing the lower body and efficiently transferring energy up the kinetic chain. Front knee extension should begin at foot plant as a result of pelvis rotation and driving your weight into your lead heel. This combination of movements not only extends the lead knee, but also stabilizes the pelvis to support torso rotation. This means that more lead knee extension at max external rotation leads to a more efficient transfer of energy from the
pelvis to the torso. Lead knee extension is the brakes of the pitching motion, which causes the lower body to decelerate and stop as the upper body accelerates forward. It is extremely difficult to rotate your torso quickly as your lower body is continuing to drift forward. Greater knee extension at MER demonstrates that a pitcher is more efficiently stabilizing their lower body, and typically that they are beginning this stabilization closer to foot plant, which is ideal for upper body kinematics.

3.4.2.5 Trunk Forward Tilt

Trunk forward tilt has been previously found to be correlated to throwing velocity [17,23,38]. One such reason for this correlation is because increasing trunk forward tilt can create a lag effect, which can increase the energy stored in the arm and ultimately transferred to the ball at release [39]. This lag effect is signified by the trunk tilting forward as the shoulder is still in horizontal abduction. This means that the elbow is lagging the torso, which creates more stretch and distance for the arm to accelerate forward thus increasing the energy created. This forward acceleration of the arm should cause the arm to be in or entering horizontal adduction at MER [38].

The other way that trunk forward tilt increases throwing velocity is through momentum. The torso is a large body segment with a large mass meaning it has the potential for a lot of momentum. By flexing the trunk forward, you are increasing the velocity of the torso in the direction of home plate, and as such increasing your momentum in the direction of the pitch.
3.4.2.6 Postural Grouping MLR

Grouping the postural metrics by plane was used to examine if pitchers are more dominant in one plane at certain checkpoints throughout the pitching motion. The findings determined that neither plane had a moderate correlation to pitch velocity, but the frontal plane appeared to contribute the least having a consistent correlation value around 0. The lack of findings here may be a direct result of all the pitchers being grouped together as compared to the findings discussed in Chapter 6: Study 4 – Differences attributed to arm slot that determined when pitchers are grouped by arm slot, they do appear to have differences between dominant planes throughout the three checkpoints.

3.5 Limitations and Future Direction

Although all metrics were examined for correlations to pitch velocity only ten postural metrics were chosen to display pitch velocity correlations in the results section. These same ten postural metrics were also used for conducting the postural grouping MLR. A better method would be to create an algorithm that conducts MLR for different combinations of single plane and mixed plane metrics to determine the MLR with the highest correlation to ball velocity. Introducing different metrics could help to produce an MLR with higher correlations raising awareness of important metric combinations for increased pitch velocity.
3.6 Conclusion

Both kinematics and postural metrics have moderate correlations to pitch velocity, but there was no dominance found by a single plane. This displays the importance of being able to move efficiently in all planes of motion. The kinematic correlations demonstrated that each plane had two moderately high correlations to pitch velocity, while both the transverse and sagittal planes were represented by the higher postural metric correlations. The results also showed that multiple segments contribute to pitch velocity showing the importance of energy transfer from segment to segment.

Now that we determined factors that are correlated to pitch velocity it is important to repeat this process with shoulder and elbow torque. Not only will we be able to determine correlations to torque, but when combined with velocity correlations we are able to determine key metrics to offset pitch velocity and torque.

Chapter 4: Study 2 - Torque Correlations and Averages

4.1 Background

The pitching motion is a volatile motion that puts extreme stresses on the body. These stresses make pitchers susceptible to injuries especially at the shoulder and elbow, which account for up to 57% of all pitcher injuries [4,40]. The elbow is especially susceptible to injuries at the ulnar collateral ligament (UCL), which connects the humerus to the ulna. This stress during the baseball season causes physiological changes of the UCL causing it to become thicker with greater laxity [41]. These adaptations are a result of elbow experiencing varus torque upwards of 75N.m during the pitching motion, of which 55% of the torque or 40.5N.m is placed on the UCL [6,15,42]. It has been found
through cadaver studies that the UCL can fail at varus torques as low as 32N.m meaning that the UCL is consistently at stresses above its failure threshold during the pitching motion [6].

Due to the large stresses experienced by pitchers they account for 90% of UCL surgeries in MLB, and cost teams hundreds of millions of dollars in salaries [40]. Elbow and shoulder surgeries cost players in the form of money, surgery, quality of life, and even their career [43]. UCL injuries range in severity from inflammation to a complete tear. A complete tear of the UCL can be surgically treated through either a UCL repair or UCL reconstruction. UCL repair involves fixing the original UCL, whereas a UCL reconstruction involves replacing the UCL with another ligament from the body.

During the cocking phase of the pitching motion the elbow is experiencing high valgus torques as the arm enters MER. To protect the elbow and maintain stability a varus torque is created to counteract the valgus torque [44]. Additionally, at this time the shoulder is experiencing large internal rotation torques due to the excessive external rotation range of motion achieved during the late cocking phase. This internal rotation torque prevents the shoulder from externally rotating too far backwards [9]. Then starting in the acceleration phase the arm horizontally adducts through deceleration. This rapid horizontal adduction is matched by a horizontal abduction torque that is used to help decelerate the arm and prevent injury [44]. All three of these torques have implications for elbow and shoulder injury based on their timing, magnitude, and direction [45-47].

Examining torque in relation to pitching postural metrics has shown correlations to shoulder external rotation at foot plant, poor timing between the torso and pelvis maximum angular velocities, an open foot position at foot plant, and shoulder abduction
at release [16,48]. Shoulder abduction at release is a metric that has been found to be related to both increased elbow and shoulder stress [49]. This shows the importance of maintaining stability at the shoulder joint, which was discussed in **Study 1 – Velocity Correlations and Averages**. Other than correlations additional research has been performed using risk analysis to determine what metrics increase the risk of injury in baseball pitchers. This analysis determined that pitchers that have early trunk rotation or more trunk rotation at foot plant have a significant risk of upper extremity surgery [50].

In terms of kinematics researchers have investigated the effect of sequencing on elbow and shoulder torque. Using the proximal to distal kinematic sequence of pelvis, torso, arm, forearm, and hand torque values were compared for pitcher groupings. The groupings were determined by if and when a pitcher deviates from the proximal to distal pattern. It was found that the most common sequence was pitchers deviating from the proximal to distal pattern closer to release. These pitchers had the highest elbow and shoulder torques as compared to the other groups that either maintained the proximal to distal pattern or deviated earlier in the pitching motion [29,30]. Maintaining a proximal to distal pattern is important for efficient energy transfer and becomes increasingly important closer to release. This demonstrates that there are different kinematic sequences observed across pitchers, but some sequences are more efficient than others and as such can decrease the risk of injury [51]. As such it is important to understand kinematics and its relationship to pitcher injury.

This study looks to expand upon previous research by performing correlations to elbow and shoulder torque. Correlations were examined on an individual basis and in relation to plane. The torques examined are the maximum elbow varus torque before
release, maximum shoulder internal rotation torque before release, and maximum shoulder horizontal abduction torque after release.

4.2 Methods

4.2.1 Torque Normalization

Previous research into elbow torque values has determined high correlations upwards of \( r = 0.75 \) to subject weight [52]. This correlation shows that as a subject increases their weight, they increase the stress on their elbow as well. This makes it very difficult to directly compare torque values across subjects, and as a result has led to the practice of normalizing torques. To remove any anatomical influence both elbow and shoulder torque is normalized to the subject height and weight [53]. To do this the torque value in N.m is divided by the subject weight multiplied by the subject height (Figure 12). The subject weight is found by multiplying their mass in kilograms by gravity \( (9.81 \text{m/s}^2) \). Subject weight multiplied by height thus results in the units of N.m, which is the same as torque. Thus, normalized torque is unitless or can be examined as a percentage of body weight multiplied by height (%BW.H).

\[
\text{Torque (\%BW \cdot H) = \frac{\text{Torque}}{\text{Height(Weight)}}} \quad (#)
\]

Figure 12: Where torque in the numerator is in N.m, height is in meters, and weight is in N.

4.2.2 Statistical Analysis

Torque statistical analysis was performed in an identical manner to that of the pitch velocity correlations in 3.2 Methods. This includes the metrics involved in planar
kinematics, postural metrics, and multiple linear regression. Statistical analysis was performed on maximum elbow varus torque before release, shoulder internal rotation torque before release, and shoulder horizontal adduction torque after release. For metrics examined before release the maximum torque was found between foot plant and release, while metrics found after release the maximum was found between release and the end of follow-through. Correlations were run on these torques for all the metrics listed in 

Appendix 2.2. Similar to the velocity correlations there weren’t many moderate correlations of 0.4 or above. The included correlations are selected postural metrics and planar kinematics. Any additional metric that did not have a correlation of 0.4 or higher was excluded from the results section.

4.3 Results

4.3.1 Averages

Table 7: Means and standard deviations of included torque values

<table>
<thead>
<tr>
<th>Value</th>
<th>Elbow Varus Torque before Release</th>
<th>Shoulder Internal Rotation Torque before Release</th>
<th>Shoulder Horizontal Abduction Torque after Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>0.066 ± 0.041</td>
<td>0.062 ± 0.029</td>
<td>0.121 ± 0.074</td>
</tr>
</tbody>
</table>

Average elbow varus torque before release, shoulder internal rotation torque before release, and shoulder horizontal abduction torque after release can be seen in Table 7. The maximum values of the elbow varus torque and the shoulder internal rotation torque before release are 0.066 and 0.062, respectively. This means that pitchers are experiencing torques that are over 6% of their body weight multiplied by their height. Using the average subject demographics in Table 1 this equates to torque values of over
92.6N.m. Shoulder horizontal adduction torque reaches almost double these values with an average torque of 0.121.

**Figure 13**: Average torque values before release. The color of the text represents the corresponding bar color. Elbow flexion torque is the blue bar, and elbow extension torque is the red bar directly under the elbow flexion torque bar.

**Figure 13** depicts the torque values for the elbow and shoulder in every plane. The highest elbow torque before release is the varus torque. In terms of the shoulder even though the internal rotation torque is the most examined it is the third lowest torque. Shoulder horizontal adduction torque is the largest shoulder torque before release with an average value over 0.1.
Comparing the torque values after release shows almost equivalent values of elbow flexion and varus torque, while shoulder horizontal abduction has the largest torque overall at 0.12. These graphs also demonstrate that pitchers can experience torques in opposite directions during a short time, which may decrease joint stability.
4.3.2 Maximum Elbow Varus Torque Before Release

<table>
<thead>
<tr>
<th>Segment</th>
<th>Sagittal</th>
<th>Frontal</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis</td>
<td>0.096</td>
<td>0.032</td>
<td>-0.099</td>
</tr>
<tr>
<td>Torso</td>
<td>0.072</td>
<td>0.022</td>
<td>0.034</td>
</tr>
<tr>
<td>Shoulder</td>
<td>0.059</td>
<td>0.120</td>
<td>0.038</td>
</tr>
<tr>
<td>Elbow</td>
<td>0.745</td>
<td>-0.035</td>
<td>-0.009</td>
</tr>
<tr>
<td>Hand</td>
<td>0.563</td>
<td>0.363</td>
<td>0.265</td>
</tr>
<tr>
<td>MLR</td>
<td>NaN</td>
<td>0.153</td>
<td>0.130</td>
</tr>
</tbody>
</table>

**Figure 15:** Correlations for planar kinematics to maximum elbow varus torque before release. Each segment metric is the maximum angular velocity of that metric in the respective plane. There is no metric for the shoulder in the sagittal plane. The MLR column is the multiple linear regression combining the metrics for each segment in each plane.

Assessing correlations to planar kinematics showed that maximum hand sagittal angular velocity had a strong correlation of 0.745 to maximum elbow varus torque. This also caused the sagittal MLR to have a correlation of 0.563. Not only did the hand have the highest correlation in the sagittal plane, but the frontal and transverse planes as well.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis</td>
<td>-0.099</td>
</tr>
<tr>
<td>Torso</td>
<td>0.034</td>
</tr>
<tr>
<td>Shoulder</td>
<td>-0.077</td>
</tr>
<tr>
<td>Elbow</td>
<td>-0.009</td>
</tr>
<tr>
<td>Hand</td>
<td>0.265</td>
</tr>
<tr>
<td>MLR</td>
<td>0.132</td>
</tr>
</tbody>
</table>

**Figure 16:** Correlations for planar kinematics to maximum elbow varus torque before release where shoulder horizontal adduction velocity replaced shoulder internal rotation velocity in the shoulder column.
Analyzing the shoulder horizontal adduction velocity only resulted in a correlation of -0.077.

<table>
<thead>
<tr>
<th>Postural Metric Correlations to Maximum Elbow Varus Torque Before Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion</td>
</tr>
<tr>
<td>Pelvic Forward Tilt</td>
</tr>
<tr>
<td>Trunk Forward Tilt</td>
</tr>
<tr>
<td>Elbow Flexion</td>
</tr>
<tr>
<td>Pelvic Rotation</td>
</tr>
<tr>
<td>Trunk Rotation</td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction</td>
</tr>
<tr>
<td>Shoulder External Rotation</td>
</tr>
<tr>
<td>Trunk Lateral Tilt</td>
</tr>
<tr>
<td>Shoulder Abduction</td>
</tr>
</tbody>
</table>

**Figure 17:** Correlations of postural metrics to maximum elbow varus torque before release at the three checkpoints of foot plant, max external rotation, and release.

Switching from planar kinematics to postural metrics did not provide much more insight into elbow varus torque as it generated very weak correlations. The highest postural correlation was 0.179 for pelvis forward tilt at release.
The final step was to examine MLR for planar postural metrics, which resulted in even smaller correlations than the postural metrics themselves. The MLR correlations were all about zero.

**4.3.3 Maximum Shoulder Internal Rotation Torque Before Release**

Figure 19: Correlations for planar kinematics to maximum shoulder internal rotation torque before release.

Sagittal hand angular velocity had the highest correlation to maximum shoulder internal rotation torque before release at 0.652. This again led to a moderate correlation.
of 0.439 for the sagittal plane MLR. Here the hand angular velocity was the highest in each plane similar to that of elbow varus torque.

**Figure 20:** Correlations for planar kinematics to maximum shoulder internal rotation torque with shoulder horizontal adduction velocity in the shoulder column.

Substituting horizontal adduction velocity resulted in a decreased shoulder transverse kinematic correlation, and an MLR correlation of only 0.049.

**Figure 21:** Correlations of postural metrics to maximum shoulder internal rotation torque at the three checkpoints.
Pelvic forward tilt had the two highest correlations to maximum shoulder internal rotation torque with an r-value of 0.170 and 0.163 at release and MER, respectively. The metric with the next highest correlation was shoulder external rotation at foot plant with $r = -0.140$. Since the correlation is negative the relationship between the metrics is an inverse relationship, so decreasing shoulder external rotation causes an increase in torque. Shoulder external rotation at MER only had a correlation of 0.002.

![Figure 22: Multiple linear regression correlations of postural metrics grouped by plane to maximum shoulder internal rotation torque at the three checkpoints.](image)

Grouping the postural metrics by plane resulted in very small correlations at all checkpoints.
4.3.4 Maximum Shoulder Horizontal Abduction Torque After Release

**Figure 23:** Correlations for planar kinematics to maximum shoulder horizontal abduction torque after release.

Maximum shoulder horizontal abduction torque has the highest overall shoulder torques as seen in **Figure 13**. This makes it the most important shoulder torque to determine correlated metrics so training adjustments can be created for pitchers to mitigate this value. Hand frontal velocity has the greatest kinematic correlation with a moderate correlation of 0.610. Hand sagittal and transverse velocities had the next highest correlations to torque. Thus decreasing hand velocity in any plane would create a corresponding decrease in torque. Kinematics especially of the distal segments are difficult to train and control in pitchers, and for this reason postural metrics pose better implications for mechanical adjustments to reduce injury risk.

**Figure 24:** Correlations for planar kinematics to maximum shoulder horizontal abduction torque, where shoulder horizontal adduction velocity replaced shoulder internal rotation velocity in the shoulder column.
Replacing shoulder external rotation velocity with horizontal adduction velocity resulted in a correlation of -0.130 and decreased the MLR value to 0.242.

Figure 25: Correlations of postural metrics to maximum shoulder horizontal abduction torque at foot plant, max external rotation, and release.

Trunk forward tilt at release has the highest correlation to maximum shoulder horizontal abduction torque with an r-value of 0.137. This positive relationship means that an increase in forward trunk tilt is related to an increase in torque although it has a weak relationship. Shoulder horizontal abduction has the second largest magnitude correlation at -0.127. Since shoulder horizontal abduction at foot plant is a negative angle a negative correlation represents a direct relationship so decreasing the angle results in a decrease in torque.
Figure 26: Multiple linear regression correlations of postural metrics grouped by plane to maximum shoulder horizontal abduction torque after release at the three checkpoints.

Planar postural metrics were close to zero for not only maximum shoulder horizontal abduction torque after release, but for all the examined torques. This shows that individual postural and kinematic metrics are more important from a training standpoint, and that all planes need to be considered when analyzing torque.

4.4 Discussion

4.4.1 Averages

The averages demonstrate that even though elbow varus torque, shoulder external rotation, and shoulder horizontal abduction torques are the most examined torques that there are torques in all planes that can contribute to injury. Even though shoulder horizontal abduction torque has the highest torque value it can be seen in Figure 13 that the shoulder frontal torque (adduction/abduction) has the second highest planar torques both before and after release. This brings attention to the potential influence of alternative torques and their potential implications for injury. Future research should be performed examining the simultaneous influence of all three torques on UCL and shoulder strain.
**Figures 13 and 14** also bring attention to the fact that a pitcher can experience torque in both directions during a short period of time. This also raises the question of how quickly transitioning from torque in one direction to the opposite direction affects the elbow and shoulder. Due to the variability across pitching mechanics each pitcher experiences different torque magnitudes that are dependent on their anatomical positioning and kinematics.

### 4.4.2 Maximum Elbow Varus Torque

#### 4.4.2.1 Kinematics

The kinematic metric with the highest correlations to maximum elbow varus torque before release was the hand sagittal angular velocity. Hand sagittal angular velocity is the speed of flexion of the wrist, which typically reaches its maximum around release. This metric is positively correlated to elbow varus torque with a correlation coefficient of 0.745. Since elbow varus torque is a positive value, this means that increasing the flexion velocity of the hand increases the elbow varus torque. This strong relationship signifies that decreasing hand flexion angular velocity should decrease elbow torque without affecting pitch velocity. This is because hand sagittal angular velocity only has a correlation of 0.093 to pitch velocity (Figure 8).

#### 4.4.2.2 Postural Metrics

Pelvis forward tilt at release and MER has the highest correlations to elbow varus torque of the postural metrics. MER has previously been found to be the point of max elbow stress demonstrating the importance of the postural metrics at this checkpoint [54].
Shoulder horizontal abduction at foot plant has the next highest correlation at -0.139. Here since horizontal shoulder abduction is a negative angle there is a direct correlation, where more horizontal abduction is associated with higher torques. This expands the injury implications of previous findings in shoulder kinetics that found that having excessive shoulder horizontal abduction angles create shoulder instability and increase the risk of injury [38]. Horizontal abduction also has a correlation of -0.338 to pitch velocity, where a negative correlation constitutes a direct relationship. Decreasing horizontal abduction too much to decrease the risk of injury may also cause a direct decrease in pitch velocity, and thus the success of the pitcher. It is important to find an angle that balances the tradeoff between velocity and torque.

4.4.3 Maximum Shoulder Internal Rotation Torque Before Release

4.4.3.1 Kinematics

Maximum shoulder internal rotation torque has the highest kinematic correlation to the sagittal angular velocity of the hand. This is like the elbow varus torque correlations before release. Thus, decreasing hand sagittal velocity not only decreases elbow kinetics, but shoulder kinetics as well. Since, hand sagittal velocity is not correlated to pitch velocity this makes it an ideal candidate to manipulate to reduce the risk of injury. Unfortunately, the speed of wrist flexion is a difficult metric to control, but due to the magnitude of the correlations even slight adjustments in velocity might provide significant decreases in torque.
4.4.3.2 Postural Metrics

Again, following the results of the elbow varus torque the postural metric with the highest correlations is pelvis forward tilt at MER and release. As discussed in 3.4.1.3 Sagittal Plane Kinematics, pelvic forward tilt allows for facilitation of spinal extension and increases the angle of the shoulder going into max external rotation [31]. This is especially important at MER as the shoulder is in an extreme range of motion leading to higher shoulder kinetics, and as such pitchers need to find a way to increase shoulder stability at this checkpoint to help combat these stresses [38]. Being able to increase shoulder stability is key to reducing joint kinetics. Additionally, unlike hand sagittal angular velocity, pelvic forward tilt is a metric that can more easily be trained.

4.4.4 Maximum Shoulder Horizontal Abduction Torque After Release

4.4.4.1 Kinematics

Unlike the previous torques the highest correlation to shoulder horizontal abduction torque after release is the frontal angular velocity of the hand, which corresponds to ulnar deviation. Transverse hand angular velocity, or pronation velocity also has a moderate correlation. Increased pronation has shown significant differences in pitcher kinetics when comparing pitch types. A fastball has increased shoulder internal rotation torque, elbow varus torque, and hand pronation when compared to a curveball [55]. This implies that there could be injury implications based on wrist positioning when pitching. Here it was found that quicker pronation is associated with an increase in torque. This shows that the speed of pronation may be just as important as the angle in terms of the influence on pitcher kinetics. All three torques examined in this study had
their highest correlations to hand angular velocity in all three planes. Hand angular velocity thus has implications for player injury, and modifications of these metrics should be implemented into pitcher training to mitigate injury.

4.4.4.2 Postural Metrics

All postural metrics had weak correlations to maximum shoulder horizontal abduction torque after release. The highest correlation was trunk forward tilt at release with a correlation coefficient of 0.137. The second highest correlation was horizontal shoulder abduction at foot plant. As discussed in 3.4.2.5 Trunk Forward Tilt, the degree of trunk forward tilt helps to facilitate shoulder horizontal abduction creating a lag effect in the arm [39]. Thus, both correlations are related to the amount of horizontal shoulder abduction created before release. Decreasing shoulder horizontal abduction before release may decrease the horizontal shoulder abduction torque after release, although it should be noted that the correlations are small. There were no postural metrics examined in this study that had a moderate correlation to any of the three torques, which demonstrates the importance of kinematic parameters in decreasing pitcher risk of injury.

4.4.5 Postural Grouping MLR

Grouping the postural metrics by plane provided no insight into injury mechanisms as all correlations for both elbow and shoulder torques were close to zero.
4.5 Limitations and Future Direction

This study only examined the relationships between three torques and pitching metrics. These are the three torques most associated with pitching injury, but it is also important to examine torque in other planes and how these torques interact. Future research is needed on the connections between torque in all three planes, and how manipulating these torques affects both the stress and the strain on the ligaments.

4.6 Conclusion

Pelvis forward tilt and trunk forward tilt are the two postural metrics that may play a small role in mitigating pitching injuries. Postural metrics only had weak correlations to torque, but by adjusting these two postural metrics through training there could be a resultant reduction in torque values thus reducing the risk of injury on both the shoulder and the elbow. Kinematic parameters on the other hand demonstrated both moderate and strong correlations, especially for the hand angular velocity. Hand sagittal angular velocity had implications for reducing all three torques but as a kinematic metric is much more difficult to adjust through training. As such pitching instructors should focus on postural metrics for the reduction of torques, while maintaining pitching velocity.

Part 1: Summary

Part 1 looked to determine postural metric and kinematic correlations to pitch velocity and torque. Postural metric groupings based on their torque and pitch velocity correlations can be found in Table 8. It was found that in terms of individual postural
metrics knee flexion and shoulder external rotation were correlated to pitch velocity. While there was no individual metric correlated with torque that wasn’t also correlated to pitch velocity. These individual metrics can thus be manipulated to gain better results for pitch velocity. Pelvis forward tilt, trunk forward tilt, and horizontal shoulder abduction were tradeoff postural metrics that by increasing it resulted in both an increase in pitch velocity and torque. Coaches should be aware of this tradeoff when instructing pitchers as making large adjustments in these metrics as they can lead to drastic changes in both pitcher velocity and torque. Additional work should be conducted to determine an optimal angle for these metrics to maximize velocity, while minimizing torque. There were no positive or negative metrics found that had an impactful inverse relationship between pitch velocity and torque.

**Table 8**: Postural Metric Groupings based on Velocity and Torque Correlations

<table>
<thead>
<tr>
<th></th>
<th>Pitch Velocity Individual Metrics</th>
<th>Torque Individual Metrics</th>
<th>Tradeoff Metrics</th>
<th>Positive Metrics</th>
<th>Negative Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder External Rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis Forward Tilt*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Forward Tilt*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* constitutes a weak relationship

Kinematics only resulted in individual metrics for pitch velocity and torques (**Table 9**). Pitch velocity had correlations to six kinematic metrics, which were sagittal
pelvis angular velocity, sagittal elbow angular velocity, frontal pelvis angular velocity, frontal shoulder angular velocity, transverse torso angular velocity, and transverse shoulder (horizontal adduction) angular velocity. Each plane of motion was represented by two kinematic parameters that were correlated to velocity. Torque metrics had their highest correlations to hand angular velocity in all three planes, with the sagittal velocity having the highest correlation to both torques before release. Decreasing hand velocity would decrease torque, but kinematic parameters are difficult to coach making it tough to adjust these metrics for their influence on pitch velocity and torque. As such postural metrics may provide an easier route for pitcher development. For additional visualizations of postural and kinematic correlations to both pitch velocity and torque values see Appendix 2.3 Comparison Heatmaps of Pitch Velocity and Torque Correlations.

Table 9: Kinematic Metric Groupings based on Velocity and Torque Correlations

<table>
<thead>
<tr>
<th>Pitch Velocity Individual Metrics</th>
<th>Torque Individual Metrics</th>
<th>Tradeoff Metrics</th>
<th>Positive Metrics</th>
<th>Negative Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal Pelvis</td>
<td>Sagittal Hand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal Elbow</td>
<td>Frontal Hand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal Pelvis*</td>
<td>Transverse Hand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal Shoulder*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse Torso</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Horizontal Adduction)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* constitutes a weak relationship
Part 2: Factors that influence postural metrics and kinematics

Now that we know which metrics are correlated to pitch velocity and torque values, we look to examine factors that may influence these metrics in terms of height, weight, age, segment lengths, arm slot, and mobility. These factors may limit or increase postural metrics, which as a result indirectly affect pitch velocity and torque. This is important as knowing a metric is correlated to pitch velocity or torque doesn’t allow us to properly make pitching mechanical adjustments without knowing a pitcher’s anatomical causation to these metrics.

Chapter 5: Study 3 – Differences attributed to height, weight, age, and segment lengths

5.1 Background

We wanted to examine how different anatomical factors affect pitching mechanics, kinematics, and kinetics. These factors are height, weight, age, and segment lengths. Height and weight have been found to both be related to pitch velocity with increasing these factors leading to an increase in pitch velocity [18,56]. Not only is weight related to pitch velocity, but it also has injury implications for both the elbow and shoulder. Weight is highly correlated to elbow varus torque in baseball pitchers, and body fat mass is correlated to shoulder distraction force in softball pitchers [52,57]. Thus, it is important to further determine what specific pitching metrics are related to weight that provide this increase in velocity and if they can be adjusted to maintain velocity, while decreasing stress on the upper extremities.

One study linked to age examined pitching differences between groups of pitchers varying in skill level from youth to professional pitchers. They found that there were
significant differences across the groups with the professional group having the largest torques, pitch velocity, and segment angular velocities [27]. These differences across skill level also represent a difference across ages as well. Other postural metrics that have significant differences across age groups include stride length, pelvis orientation, maximum shoulder external rotation, lead knee flexion, and trunk forward tilt [58]. Differences within these metrics may not be due to age directly, but factors associated with age such as height, weight, and segment lengths.

There are significant differences in both humerus length and radius length between high and low velocity pitchers [56]. We wanted to take this research a step further by examining the direct correlations between similar factors and pitching mechanics. Segment lengths that were extracted from Visual 3D for testing were the left upper arm (humerus length), right upper arm, thorax, left thigh (femur length), and right thigh. These segments were chosen as representative moment arms that provide leverage for a pitcher. Longer moment arms are thought to increase angular velocity and force, by increasing the distance from the pivot point. As such it is thought that taller pitchers or pitchers with longer levers would have an anatomical advantage. This theory was tested through the examination of these anatomical factors in relation to postural metrics, angular velocities, forces, and torques.

5.2 Methods

5.2.1 Segment Lengths

Segment lengths in this study were exported from Visual 3D, and as such were determined based on the distance between marker placement on anatomical landmarks.
The segments that were able to be exported from Visual 3D were the right thigh, left thigh, right upper arm, left upper arm, and the torso. In addition to linear regression as right and left segments the upper arm was also recategorized as pitching arm. The pitching arm metric took the left upper arm length for left-handed pitchers and the right upper arm length for right-handed pitchers to give a better representation of how this length may affect pitching mechanics.

5.2.2 Statistical Analysis

Linear regression was performed following the steps outlined in 3.2 Methods. Linear regression was used to determine the Pearson’s correlation coefficient for various metrics. In this study height, weight, age, and segment lengths were analyzed for correlations both to each other and against all the metrics listed in Appendix 2.2 excluding the kinetic metrics. Kinetic variables were excluded because torque values were normalized for height and weight. Correlations were used to determine if any pitching metrics were affected by anthropomorphic values.
5.3 Results

Figure 27: Correlations greater than 0.4 for height. Height correlations were run for all postural and kinematic values. Height has the highest correlation to arm slot, but is also correlated to lateral trunk tilt, lateral pelvic tilt at foot plant, and hip-shoulder separation at release.

Pitcher height was found to have most of its correlations in the frontal plane. This was coming in the form of lateral trunk tilt and lateral pelvic tilt. The high inverse correlation of height and lateral trunk tilt at release ($r = -0.565$) directly corresponds to the high direct correlation to arm slot ($r = 0.602$) as lateral trunk tilt is used to create a pitcher’s arm slot. Height was not found to be correlated to pitch velocity.
Weight was found to be correlated to pitch velocity with a correlation coefficient of $r = 0.487$. This leads to the idea that the more mass you have the harder you can throw. Weight was also found to be negatively correlated to lead knee frontal angle at release ($r = -0.439$). A positive knee frontal angle is indicative of valgus, and a negative angle is varus. This demonstrates that heavier pitchers tend to bow their knee inward at release, while lighter pitchers bow their legs outward.

**Figure 28**: Correlations greater than 0.4 for weight. Weight was found to be correlated to pitch velocity, and valgus knee angle at release (varus is positive and valgus is negative).

**Figure 29**: Age was found to be correlated to pitch velocity.
Age had the highest correlation to pitch velocity of the three metrics with $r = 0.567$.

![Figure 30: Of the three main metrics it was found that height had the highest correlation to weight, and weight had similar correlations to both height and age.](image)

Examining the relationship between the three metrics of height, weight, and age found that height had the highest correlation to weight ($r = 0.426$) and a low correlation to age ($r = 0.168$). Weight had similar correlations to both height ($r = 0.426$) and age ($r = 0.487$).
Figure 31: Correlations for trunk length. Trunk length was correlated to the postural metrics of lateral trunk tilt and arm slot, and correlated to the anatomical metrics of height and weight.

The only segment to be correlated to postural metrics of that segment was trunk length, which was correlated to trunk lateral tilt at foot plant ($r = -0.401$). Trunk length was also correlated to height ($r = 0.573$) and arm slot ($r = 0.442$), which corresponds to the findings that height was correlated to both lateral trunk tilt and arm slot. Trunk length was also found to be correlated to weight ($r = 0.588$), which was also previously found to be correlated to height. A longer trunk appears to be associated with a taller and heavier pitcher that has a more horizontal arm slot. No segment lengths were found to be correlated to kinetics, or their respective kinematics.
5.4 Discussion

5.4.1 Height

Height has been found to be correlated to metrics that constitute arm slot. This is seen in its correlation to lateral trunk tilt at various points throughout the pitching motion and being correlated to arm slot itself. Pitchers that are taller tend to have a higher angle arm slot, which corresponds to a more horizontal slot. When paired with the arm slot results discussed later in this study (Chapter 6: Study 4 – Differences attributed to arm slot) it may suggest that taller pitchers move better in the transverse plane, and as such when learning how to pitch the body organizes itself into a lower arm slot. This has interesting implications for training and future studies looking further into the anatomy of these pitchers such as the type of mover the pitcher is, their stability in different planes and how that affects their arm slot. Taller pitchers also have more lateral pelvic tilt at foot plant, which coincides with their lateral trunk tilt. Not much research has been conducted into lateral pelvic tilt of pitchers, but it may be a lower half stabilization mechanism.

5.4.2 Weight

Weight was only found to be correlated to pitch velocity, and the frontal angle of the knee (varus/valgus). The correlation between weight and ball velocity agrees with previous research [18,56]. Weight being correlated to velocity corresponds to the adage that “mass equals gas”, or that putting on weight will allow a pitcher to throw harder. There is evidence that this is true, but the type of mass may be important. Increasing weight by gaining muscle through training is different than gaining body fat. Training not only increases weight but can also increase other important variables for pitching such as
strength, power, proprioception, and stability. Adding body fat to gain velocity has implications for injury. A recent study in softball pitchers found that higher body fat mass was associated with an increase in shoulder distraction force ($r=0.822$) [57]. This means that the more body fat a pitcher has the more force that their shoulder is going to experience, and the greater their likelihood for injury. Other studies have found similar results with pitcher weight being associated with increased elbow varus torque [52,59]. We did not duplicate these findings as the torque values were not examined in this study because they were normalized for both height and weight to better compare across pitchers.

The other metric found to be correlated to weight in this study was the frontal angle of the knee, which is the varus or valgus angle of the knee. Heavier pitchers tend to have a more valgus knee angle at release as compared to lighter pitchers meaning that their knee is angled inward. Research into the deceleration phase of a single leg drop vertical jump has found that people who land with a valgus knee have a significantly higher angular impulse at their knee than people who land with a varus angle [60]. Since pitchers are also going into the deceleration phase at release a more valgus angle here may also cause higher angular impulse, and thus be a concern for knee injuries in pitchers.

5.4.3 Age

Age was only found to be correlated to pitch velocity, which could be a direct result of physical development or a longer duration of pitching training.
5.4.4 Interactions of Height, Weight, and Age

Height, weight, and age are all metrics that can affect pitching and are thought to be related. Height was found to be correlated to weight, but only had a low correlation to age. On the other hand, weight was found to have a similar correlation to both height and age. These correlations demonstrate that as you get older you have a trend for weight increase, but not necessarily an increase in height. This is most likely due to the fact that most of the pitchers included in this study were already fully developed, and as such have reached their max height. So, at this point age wouldn’t be correlated to height as you are limited by your genetics. Age is correlated to weight though as even though you are not growing taller you can still increase your mass over the years.

5.4.5 Segment Length

No segment lengths were found to be correlated to kinetics or their respective kinematics, which goes against the lever arm theory. This could be because only certain segments were examined instead of the whole arm or could also be a result of pitching efficiency. Pitchers with longer levers may have the potential for higher angular velocities, but they may not be reaching this potential due to mechanical inefficiencies within their motion. Trunk length was the only segment length to be correlated to one of its postural metrics in the form of lateral trunk tilt. This demonstrated that taller pitchers had less trunk tilt toward their glove side meaning that they threw with a more neutral posture or even favored their arm side at foot plant. Pitchers with a longer torso also favored a lower or more horizontal arm slot as compared to pitchers with a shorter trunk
throwing more over the top. Seemingly because of anatomical proportions pitchers with a longer trunk were also taller and weighed more.

5.5 Limitations and Future Direction

Most of the pitchers used in this study were college age thus it would be beneficial to have a more diverse group of pitchers in terms of age to get a better picture of how age affects pitching mechanics. In this study it was found that heavier players had a higher pitch velocity, but a future study is needed examining the relationship between pitcher weight, muscle mass, and body fat composition to determine how different body compositions affect pitching mechanics.

An additional limitation was only being able to extract five segment lengths from Visual 3D, which only gave small insight into the influence of segment lengths on pitching mechanics. Examining a complete list of segment lengths would be beneficial especially for segments such as the arm that gains leverage from both the humerus and forearm.

5.6 Conclusion

Height, weight, age, and the tested segment lengths did not show much correlation to pitching mechanics or kinematics. Height and trunk length were both correlated to arm slot, with taller pitchers typically showing a more horizontal arm slot. This finding may provide additional information into how the body self organizes and generates energy at different heights. Additionally, duplicating previous research weight
was found to be correlated with ball velocity, which suggests the importance of weight training and physical development in pitching.

Chapter 6: Study 4 – Differences attributed to arm slot

6.1 Background

The pitching motion is a complex and ballistic motion that requires intricate timing of anatomical segments moving at high speeds. The linking of segments is key to transfer energy from one segment to the next, and ultimately ending up into the ball at release. How and when these segments are linked is dependent on pitching mechanics, which are unique to an individual. Each pitcher has their own mechanical style that works best for them. This style can be dependent on mobility, anatomy, coaches, and comfort. One main feature to a pitcher’s mechanics is their arm slot. Arm slot refers to the angle of the arm at release with respect to a vertical axis (Figure 32). A pitcher’s arm slot is determined early on in their pitching career and when not modified by coaching is the arm position that feels most natural to a player. Arm slot has implications on ball movement, and

Figure 32: Depiction of the arm slot angle at release.
as such can define a pitcher’s pitch movement profile. There are three main categories of arm slots that are recognized by the baseball community, which are overhand, three-quarter, and sidearm in order of most to least vertical.

Previous studies have been performed looking at the differences between these three groups in terms of postural metrics, kinematics, and kinetics. It has been found that there are significant differences in maximum pelvis angular velocity, trunk forward tilt at foot plant and release, trunk rotation, maximum shoulder external rotation, trunk lateral tilt at release, shoulder abduction at release, and elbow flexion at foot plant and release [61,62]. Additionally in terms of kinetics having a more horizontal slot corresponds to an increase in elbow varus torque [63-65]. This demonstrates that arm slot not only affects pitching mechanics, but also the corresponding torques and forces, which could make certain arm slots more prone to injury. Overhand pitchers exhibit decreased elbow flexion torque, while sidearm pitchers have the lowest shoulder anterior force [61]. Arm slot may provide further insight into specific areas of injury with the overhand pitchers having a more at-risk shoulder, and the sidearm pitchers being more at risk at the elbow.

The purpose of this study is to determine a method to calculate arm slot based on anatomical angles and lengths and examine planar differences between arm slot groups. Different arm slot groups appear to have different dominant anatomical planes of their pitching motion. A dominant anatomical plane during the pitching motion is the plane that contributes most to ball velocity throughout the pitching motion. The dominant plane can either be the sagittal, frontal, or transverse, where it is thought that a pitcher’s arm slot would both mimic and affect their dominant plane of motion. The more vertical arm slot seen in overhand pitchers visually appears to incorporate more sagittal movements
such as trunk flexion, while sidearm pitchers whose arm is more horizontal appear to use less flexion and more rotation to obtain their ball velocity. As such it is thought that the overhand pitchers would be sagittal plane dominant, sidearm pitchers would be transverse plane dominant, and three-quarter would be a combination of both. We look to determine the differences between each arm slot group and the dominant plane of motion for each by examining their angles and angular velocities in all three planes.

6.2 Methods

6.2.1 Calculating Arm Slot

To calculate arm slot based on the collected data I used three geometric equations. The angles of the elbow, trunk lateral tilt, and shoulder abduction were all pulled from the mocap data at the point of release. In addition to these angles the length of the humerus and the forearm were also needed. To estimate these segment lengths proportions based on each subject’s height from Drillis and Contini were used (Figure 33) [66].
The lengths of the upper arm and forearm where then used as the sides of a triangle created by the arm (Figure 34). Using the law of cosines combined with the elbow extension angle provided the length of the hypotenuse of the triangle, which is also the vector that connects the shoulder joint to the wrist. This length in combination with the law of sines resulted in the angle of the arm. Since the trunk is laterally tilted into release to determine the angle from the upper arm to the horizontal axis, we needed to combine the angle of the trunk lateral tilt with the shoulder abduction angle. By subtracting 90° from the shoulder abduction angle at release we were able to determine where the upper arm was with respect to the lateral trunk tilt. To determine the arm slot angle we subtracted the

\[ H_{Len} = \sqrt{U_{Len}^2 + F_{Len}^2 - 2U_{Len}F_{Len} \cos \theta_{Eib}} \] (4)

\[ \theta_{Arm} = \sin^{-1}\left(\frac{F_{Len} \sin \theta_{Eib}}{H_{Len}}\right) \] (5)

**Figure 34:** Arm angle geometric equations. Where \( U_{Len} \) is the length of the upper arm, \( F_{Len} \) is the length of the forearm, \( H_{Len} \) is the length of the hypotenuse, and \( \theta_{Eib} \) is the elbow extension angle at release.

\[ \theta_{Slot} = 90 - (\theta_{Arm} + \theta_{TL} + (\theta_{SHA} - 90)) \] (5)

**Figure 35:** Arm slot angle. Where \( \theta_{Slot} \) is the arm slot angle, \( \theta_{Arm} \) is the angle of the arm vector, \( \theta_{TL} \) is the angle of trunk lateral tilt at release, and \( \theta_{SHA} \) is the angle of shoulder abduction at release.
arm, trunk, and relative shoulder abduction angle from 90° (Figure 35). All arm slot
angles were approximated from the rear view of the pitcher at release using these
equations.

6.2.2 Arm Slot Groups

<table>
<thead>
<tr>
<th></th>
<th>Overhand (&lt;40°)</th>
<th>Three-quarter (40°-60°)</th>
<th>Sidearm (&gt;60°)</th>
</tr>
</thead>
</table>

Figure 36: Skeletal example of each type of arm slot at the moment of release.

Arm slot is the angle of the arm at release with respect to a vertical axis. Most
pitchers fall into one of three categories: overhand, three-quarter, and sidearm. Overhand
pitchers have a more vertical arm slot, sidearm pitchers have a more horizontal arm slot,
and three-quarter pitchers fall somewhere in-between the other two groups. Definitions of
arm slot groups based on angle have previously been defined as overhand being less than
40°, three-quarter 50°-60°, and sidearm greater than 70°, where the angle was defined as
the difference between the vertical axis and a vector that connected the center of the
shoulder joint to the hand [61]. An arm slot of 0° would be a straight vertical arm, and an
arm slot of 90° would be holding your arm out to the side in line with your shoulder. In
this study arm slots were defined as overhand less than 40°, three-quarter 40°-60°, and
sidearm greater than 60°. Filling in the gaps in the arm angle ranges allowed all subjects to be used in this study. Of the 62 pitchers in this study there were 23 overhand pitchers, 32 three-quarter slot pitchers, and only 7 sidearm pitchers.

6.2.4 Statistical Analysis

To determine differences between the three groups a one-way ANOVA was performed with $\alpha = 0.05$. This was followed by a Bonferroni correction, which was used to determine the differences between group pairs. Within group correlations to ball velocity were also performed to determine the five metrics with the highest correlation that occurred at or after foot plant. Multiple linear regression was also used to determine which combination of planes of motion for each major segment led to the highest correlation with velocity. The five major segments are the pelvis, trunk, shoulder, elbow, and hand. MLR was performed for ball velocity for every planar combination of angular velocity for all five major segments. This means that each combination contained all five segments represented by either the sagittal, frontal, or transverse angular velocity for that segment. Combination examples would be the MLR for the angular velocity of all five segments in the transverse plane, or a second example of the pelvis transverse angular velocity, trunk sagittal angular velocity, shoulder frontal angular velocity, elbow sagittal angular velocity, and hand transverse angular velocity. So, each segment is represented once by its angular velocity in one of the three planes of motion. The MLR with the highest correlation to ball velocity was then chosen for the overhand and three-quarter arm slot groups. Due to the small sample size of the sidearm group almost all
combinations had a high correlation to ball velocity, and as such it was excluded from the MLR results.

MLR was also performed to determine the dominant plane of motion for each arm slot group. The correlation for ball velocity was made using ten postural metrics that are commonly examined in pitching motion capture (Table 4). Of these ten metrics four were in the transverse plane, four were in the sagittal plane, and two were in the frontal plane. The correlation was found for the metrics in each plane against ball velocity at foot plant, max external rotation, release, and when using all three time points.

6.3 Results

6.3.1 ANOVA Results

Table 10: Arm Slot ANOVA Kinematic Metrics

<table>
<thead>
<tr>
<th>Kinematic Parameter</th>
<th>Overhand</th>
<th>Three-quarter</th>
<th>Sidearm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Sagittal Torso Angular Velocity**</td>
<td>299.9°/s(^b)</td>
<td>281.9°/s(^c)</td>
<td>206.5°/s(^b,c)</td>
</tr>
<tr>
<td>Maximum Transverse Pelvis Angular Velocity***</td>
<td>637.9°/s(^b)</td>
<td>674.3°/s(^c)</td>
<td>776.2°/s(^b,c)</td>
</tr>
<tr>
<td>Transverse Pelvis Angular Velocity at Release**</td>
<td>47.49°/s</td>
<td>99.10°/s(^c)</td>
<td>-45.45°/s(^c)</td>
</tr>
</tbody>
</table>

\* = p < 0.05, \** = p < 0.01, \*** = p < 0.001
\(a = p < 0.05\) for Overhand and Three-quarter, \(b = p < 0.05\) for Overhand and Sidearm, \(c = p < 0.05\) for Three-quarter and Sidearm

In terms of kinematics there were three metrics that had differences between the groups. Maximum sagittal torso angular velocity, maximum transverse pelvis angular velocity, and transverse pelvis angular velocity at release were all significantly different
between the groups. Post-hoc testing showed that in terms of kinematics there were no significant differences between the overhand and the three-quarter arm slot groups, but both these groups had differences with the sidearm group.

**Table 11: Arm Slot ANOVA Pelvis Metrics**

<table>
<thead>
<tr>
<th>Pelvis Parameter</th>
<th>Overhand</th>
<th>Arm Slot</th>
<th>Sidearm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvic Forward Tilt at Leg Lift*</td>
<td>-11.95°</td>
<td>-8.791°</td>
<td>-1.613°</td>
</tr>
<tr>
<td>Pelvic Forward Tilt at Foot Plant*</td>
<td>12.98°</td>
<td>9.664°</td>
<td>18.85°</td>
</tr>
<tr>
<td>Pelvic Lateral Tilt at Foot Plant**</td>
<td>-6.821°</td>
<td>-10.18°</td>
<td>-15.73°</td>
</tr>
<tr>
<td>Pelvis Rotation at Max External Rotation**</td>
<td>-4.803°</td>
<td>-9.153°</td>
<td>-21.35°</td>
</tr>
</tbody>
</table>

* = p < 0.05, ** = p < 0.01, *** = p < 0.001  

a = p < 0.05 for Overhand and Three-quarter, b = p < 0.05 for Overhand and Sidearm,  
c = p < 0.05 for Three-quarter and Sidearm

Four pelvic parameters resulted in significant differences between the groups, but again there were no significant differences between the overhand and three-quarter arm slot groups. The overhand group was significantly different from the sidearm group in terms of pelvic forward tilt, or pelvic anterior tilt at leg lift, pelvic lateral tilt at foot plant, and pelvis rotation at max external rotation. The three-quarter arm slot group was found to be significantly different from the sidearm group in terms of pelvic forward tilt at foot plant and pelvis rotation at max external rotation.
The trunk is an important contributor to energy during the pitching motion and has major implications in all three planes unlike some of the other segments. The trunk also helps to set up arm slot through lateral tilt, and as such explains why all three groups are significantly different from each other in terms of trunk lateral tilt at all time points. There also appears to be relationship between trunk forward tilt and trunk lateral tilt, with the groups that have more lateral tilt also having more forward tilt and vice versa.

<table>
<thead>
<tr>
<th>Trunk Parameter</th>
<th>Overhand</th>
<th>Three-quarter</th>
<th>Sidearm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Forward Tilt at Leg Lift*</td>
<td>-12.06°[^a,b]</td>
<td>-12.51°[^c]</td>
<td>-2.546°[^a,b,c]</td>
</tr>
<tr>
<td>Trunk Lateral Tilt at Leg Lift***</td>
<td>-2.605°[^a,b]</td>
<td>-6.067°[^c]</td>
<td>-16.85°[^a,b,c]</td>
</tr>
<tr>
<td>Trunk Forward Tilt at Foot Plant*</td>
<td>-3.780°[^a]</td>
<td>-4.287°[^c]</td>
<td>5.097°[^c]</td>
</tr>
<tr>
<td>Trunk Lateral Tilt at Foot Plant***</td>
<td>16.24°[^a,a,b]</td>
<td>6.871°[^a,c]</td>
<td>-10.74°[^a,b,c]</td>
</tr>
<tr>
<td>Trunk Lateral Tilt at Max External Rotation***</td>
<td>29.75°[^a,a,b]</td>
<td>21.10°[^a,c]</td>
<td>5.184°[^a,b,c]</td>
</tr>
<tr>
<td>Trunk Rotation Angle at Max External Rotation***</td>
<td>19.96°[^a,b]</td>
<td>13.83°[^c]</td>
<td>-5.96°[^a,b,c]</td>
</tr>
<tr>
<td>Trunk Lateral Tilt at Release***</td>
<td>35.06°[^a,a,b]</td>
<td>26.29°[^a,c]</td>
<td>9.789°[^a,b,c]</td>
</tr>
<tr>
<td>Trunk Rotation at Release***</td>
<td>2.523°[^a,b]</td>
<td>-1.805°[^c]</td>
<td>-20.06°[^a,b,c]</td>
</tr>
</tbody>
</table>

[^a]: p < 0.05 for Overhand and Three-quarter, b = p < 0.05 for Overhand and Sidearm, c = p < 0.05 for Three-quarter and Sidearm

The trunk is an important contributor to energy during the pitching motion and has major implications in all three planes unlike some of the other segments. The trunk also helps to set up arm slot through lateral tilt, and as such explains why all three groups are significantly different from each other in terms of trunk lateral tilt at all time points. There also appears to be relationship between trunk forward tilt and trunk lateral tilt, with the groups that have more lateral tilt also having more forward tilt and vice versa.
Table 13: Arm Slot ANOVA Lead Knee Metrics

<table>
<thead>
<tr>
<th>Lead Knee Parameter</th>
<th>Arm Slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Knee Flexion Angle at Foot Plant*</td>
<td>Overhand 34.28°&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

* = p < 0.05, ** = p < 0.01, *** = p < 0.001
a = p < 0.05 for Overhand and Three-quarter, b = p < 0.05 for Overhand and Sidearm, c = p < 0.05 for Three-quarter and Sidearm

The lead knee position at foot plant is different for the sidearm group than the other two groups and may be the result of a different landing technique.

Table 14: Arm Slot ANOVA Arm Metrics

<table>
<thead>
<tr>
<th>Arm Parameter</th>
<th>Arm Slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder External Rotation at Release*</td>
<td>Overhand 94.90°</td>
</tr>
<tr>
<td>Elbow Flexion Angle at Max External Rotation*</td>
<td>90.65°&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

* = p < 0.05, ** = p < 0.01, *** = p < 0.001
a = p < 0.05 for Overhand and Three-quarter, b = p < 0.05 for Overhand and Sidearm, c = p < 0.05 for Three-quarter and Sidearm

In terms of arm metrics there is a significant difference between the overhand and three-quarter arm slot groups in terms of elbow flexion at MER. There are no significant differences between the sidearm group and any other group. There is a significant difference in shoulder external rotation at release overall, but examination between pairs shows no significant difference.
**Table 15**: Arm Slot ANOVA Hip-Shoulder Separation Metrics

<table>
<thead>
<tr>
<th>Hip-Shoulder Separation Parameter</th>
<th>Overhand</th>
<th>Arm Slot</th>
<th>Sidearm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Tilt Hip-Shoulder Separation at Foot Plant***</td>
<td>-21.41ªª</td>
<td>-14.19ª</td>
<td>-4.484ªb</td>
</tr>
<tr>
<td>Forward Tilt Hip-Shoulder Separation at Max External Rotation*</td>
<td>-23.29ª</td>
<td>-17.56ª</td>
<td>-14.82ª</td>
</tr>
<tr>
<td>Lateral Tilt Hip-Shoulder Separation at Max External Rotation***</td>
<td>20.03ªª</td>
<td>12.37ªª</td>
<td>2.084ªb,c</td>
</tr>
<tr>
<td>Rotational Hip-Shoulder Separation at Max External Rotation*</td>
<td>30.23ªb</td>
<td>28.25ª</td>
<td>17.66ªb</td>
</tr>
<tr>
<td>Lateral Tilt Hip-Shoulder Separation at Release***</td>
<td>29.47ªª</td>
<td>20.32ªª</td>
<td>9.191ªb,c</td>
</tr>
</tbody>
</table>

* = p < 0.05, ** = p < 0.01, *** = p < 0.001
ª = p < 0.05 for Overhand and Three-quarter, b = p < 0.05 for Overhand and Sidearm, c = p < 0.05 for Three-quarter and Sidearm

Hip-shoulder separation is the difference between the torso and pelvis angle in each plane. The lateral tilt hip-shoulder separation will thus be related to the lateral trunk tilt, and as such arm slot. Therefore, there are significant differences between all three groups in terms of lateral tilt hip-shoulder separation. There are also differences between the overhand and sidearm groups in terms of rotational hip-shoulder separation, which is an important metric for energy transfer.
6.3.2 Correlations to Ball Velocity

Table 16: Overhand pitchers five highest correlations to ball velocity

<table>
<thead>
<tr>
<th>Metric</th>
<th>Correlation Coefficient</th>
<th>Plane of Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Sagittal Elbow Angular Velocity***</td>
<td>0.7260</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Maximum Frontal Torso Angular Velocity***</td>
<td>0.6979</td>
<td>Frontal</td>
</tr>
<tr>
<td>Maximum Pitcher Shoulder External Rotation***</td>
<td>0.6933</td>
<td>Transverse</td>
</tr>
<tr>
<td>Pelvis Anterior Tilt at Release**</td>
<td>0.6616</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Torso Forward Tilt at Release*</td>
<td>0.4450</td>
<td>Sagittal</td>
</tr>
</tbody>
</table>

* = p < 0.05, ** = p < 0.01, *** = p < 0.001

Three of the five highest correlations to ball velocity of overhand pitchers are in the sagittal plane, which includes maximum sagittal elbow angular velocity with the highest correlation at $r = 0.726$, pelvis anterior tilt at release, and torso forward tilt at release.
Table 17: Three-quarter pitchers five highest correlations to ball velocity

<table>
<thead>
<tr>
<th>Metric</th>
<th>Correlation Coefficient</th>
<th>Plane of Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis Anterior Tilt at Release***</td>
<td>0.6515</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Pelvis Anterior Tilt at Max External Rotation*</td>
<td>0.5211</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Maximum Elbow Sagittal Angular Velocity**</td>
<td>0.4597</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Maximum Pelvis Sagittal Angular Velocity**</td>
<td>0.4369</td>
<td>Sagittal</td>
</tr>
<tr>
<td>Maximum Torso Transverse Angular Velocity**</td>
<td>0.4206</td>
<td>Transverse</td>
</tr>
</tbody>
</table>

* = p < 0.05, ** = p < 0.01, *** = p < 0.001

The three-quarter arm slot group has four of its five highest correlations to ball velocity in the sagittal plane, and three of the five metrics being kinematic metrics. Pelvis anterior tilt is the only postural metric and held the top two highest correlations to ball velocity with $r = 0.652$ and $r = 0.521$ at release and max external rotation respectively.
Table 18: Sidearm pitchers five highest correlations to ball velocity

<table>
<thead>
<tr>
<th>Metric</th>
<th>Correlation Coefficient</th>
<th>Plane of Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitching Elbow Valgus Angle at Foot Strike</td>
<td>0.9113</td>
<td>Frontal</td>
</tr>
<tr>
<td>Pitching Shoulder External Rotation at Foot Strike</td>
<td>0.9094</td>
<td>Transverse</td>
</tr>
<tr>
<td>Maximum Shoulder Frontal Angular Velocity</td>
<td>0.8080</td>
<td>Frontal</td>
</tr>
<tr>
<td>Frontal Hip-Shoulder Separation at Max External Rotation</td>
<td>0.8062</td>
<td>Frontal</td>
</tr>
<tr>
<td>Lead Knee Internal Rotation at Max External Rotation</td>
<td>0.6793</td>
<td>Transverse</td>
</tr>
</tbody>
</table>

* = p < 0.05, ** = p < 0.01, *** = p < 0.001

The sidearm group resulted in four highly correlated metrics that aren’t commonly studied. These metrics are the elbow valgus angle, which had the highest correlation of \( r = 0.911 \), maximum shoulder frontal angular velocity, frontal hip-shoulder separation at MER, and lead knee internal rotation at MER. These uncommon metrics may be a result of the low sidearm sample size and should be studied further in the future.

6.3.3 Kinematic Multiple Linear Regression

Overhand (\( r = 0.694 \)):

\[
Velocity = 48.6 - 0.031 \times Pelvis_{Front} + 0.0560 \times Torso_{Front} + 0.0151 \times Elbow_{Sag} - 0.0031 \times Shoulder_{Trans} + 0.002 \times Hand_{Front}
\]

Three-Quarter (\( r = 0.544 \)):

\[
Velocity = 47.4 + 0.012 \times Pelvis_{Front} + 0.0149 \times Torso_{Trans} - 0.004 \times Elbow_{Front} + 0.008 \times Shoulder_{Sag} + 0.001 \times Hand_{Trans}
\]
The kinematic multiple linear regression resulted in very different results for the overhand group as compared to the three-quarter group. Both groups included the maximum pelvis frontal angular velocity, but that was their only commonality. The overhand results showed more of a focus on the frontal plane with three of the five segments having frontal kinematics, while the three-quarter group had equal contributions between the frontal and transverse plane. Neither MLR resulted in the normally studied kinematic sequence of the pelvis, torso, and shoulder being in the transverse plane, and the elbow and hand in the sagittal plane.

6.3.4 Planar Multiple Linear Regression

**Figure 37:** Heatmap of the correlations to ball velocity of planar postural metrics at foot plant, max external rotation, release, and overall. Overall is a combination of the metrics over all three time points.
Overhand pitchers have almost identical overall correlations for the transverse ($r = 0.658$) and sagittal ($r = 0.646$) planes. These pitchers also transition from a more transverse technique at foot plant to a more sagittal dominant strategy at release. This is seen by the decreasing correlations in the transverse plane from foot plant to release, and the increasing correlations for the sagittal plane. The sidearm pitchers follow the opposite trend starting more sagittal dominant and ending more transverse dominant. The sidearm group because of its sample size was found to have an overall correlation of $r = 1$ for all three planes. The three-quarter arm slot group did not follow the same trend as the other groups as it relied more on a combination of sagittal and transverse movements throughout the pitching motion. The three-quarter group did rely more heavily on the sagittal plane though as seen by it having the highest correlations at both release ($r = 0.469$) and overall ($r = 0.670$).

6.4 Discussion

6.4.1 ANOVA

6.4.1.1 Kinematics

Pelvis, torso, elbow, shoulder, and hand angular velocities were all examined in the sagittal, frontal, and transverse planes for differences between arm slots. There were three differences in kinematics between the groups which were maximum sagittal torso angular velocity, maximum transverse pelvis velocity, and transverse pelvis angular velocity at release. Maximum sagittal torso angular velocity was greatest for the overhand group and is thought to be a direct result of overhand pitchers using more sagittal plane mechanics. The sidearm group has the lowest maximum sagittal torso angular velocity and may be due to this group trying to keep their trunk more still in the
sagittal plane and gain velocity in the transverse plane. The sidearm group did have the fastest maximum transverse pelvis angular velocity meaning that they are able to generate a lot of rotational energy with their pelvis, and replicates results of a previous study [61]. This would put the sidearm pitchers in a better position to transfer more rotational energy up the kinetic chain. The amount of energy transferred depends on the efficiency of their up-chain mechanics.

To help transfer this energy up the chain a pitcher must be able to decelerate their previous segment to allow that energy to transfer into the acceleration of the successive segment. One way to check the efficiency of the deceleration of the pelvis is through its angular velocity at release. Proper segment deceleration is important for both stabilization and acceleration of the subsequent segment [67]. An angular velocity close to zero signifies proper deceleration as the pelvis is stable and at rest. It was found that the sidearm group began to counter rotate their pelvis at release, which signifies an efficient deceleration of the pelvis but may be mistimed. In baseball hitting you do not want pelvis counter rotation until just after contact, and I believe the same would be true for pitching. Having the pelvis moving in the opposite direction of the torso near release would not only create slack in the core but would also create some counter momentum they may affect stability at the time of release.

6.4.1.2 Pelvis

Sidearm pitchers have more of an anterior pelvic tilt at both leg lift and foot plant. Posterior pelvic tilt during the stride phase (between leg lift and foot plant) signifies a good hip hinge and use of the gluteus maximus and hamstrings as the pitcher moves down the mound [68]. Having more of an anterior tilt may signify less reliance on their
hamstrings or a more quadricep (quad) dominant strategy during the stride phase [69].

Pelvis rotation at max external rotation also shows that the pelvis has past home plate (0°) for all three groups but has the most over rotation for the sidearm group. This may be a result of the rotational nature of the sidearm delivery.

### 6.4.1.3 Trunk

Trunk lateral tilt is used in combination with shoulder abduction to create a pitcher’s arm slot. To create shoulder stability a pitcher wants to maintain 90° of shoulder abduction throughout their pitching motion, and if done so then a pitcher’s arm slot is almost identical to their trunk lateral tilt subtracted from 90°. The correlation between trunk lateral tilt and arm slot is -0.782 with more lateral tilt signifying a lower arm slot angle. This explains the significant differences in trunk lateral tilt between groups found throughout the pitching motion. Since overhand pitchers have a more vertical arm slot, they need to create more lateral trunk tilt to obtain this slot, while sidearm pitchers on the other hand tend to have very little trunk lateral tilt. Trunk lateral tilt is positive when a pitcher is leaning towards their glove side meaning that their throwing arm is higher than their glove arm. Sidearm pitchers spend more time during the pitching motion tilted toward their throwing arm side than the other pitching groups, which can be seen in their negative trunk lateral tilt at both leg lift and foot plant. Overhand and three-quarter pitchers tend to start tilted toward their throwing arm but switch to a glove-side tilt by foot plant.

Overhand and three-quarter slot pitchers also lean backwards at both leg lift and foot plant as seen by their negative forward trunk tilt. This may help these groups get
more sagittal torso angular velocity by having more range to flex their trunk after foot plant. Sidearm pitchers being more rotational in the transverse plane is also seen in their trunk rotation angles. Sidearm pitchers are already rotated past home plate (0°) by max external rotation, which means that their torso is facing more towards the dugout of their arm side by release. This can be categorized as over rotation, but also might be a method for sidearm pitchers to gain some extension on their pitch by allowing their arm to be more forward at release. The higher the arm slot vertically the less rotated the torso is at release.

6.4.1.4 Lead Knee

It was also found that sidearm pitchers land with more knee extension than the other two groups. As a result, the overhand and three-quarter slot pitchers could exhibit larger knee extensor and quadricep moments, while decreasing both their vertical and posterior shear forces of the stride leg [70]. Posterior ground reaction forces have previously been reported as correlated to pitch velocity, which may cause the landing technique of these pitchers to be at a velocity disadvantage [71].

6.4.1.5 Arm

Shoulder external rotation at release is important for velocity as it allows a pitcher to carry the ball a greater distance from max external rotation to release, and as such allows more force to be applied to the ball. Therefore, having more shoulder internal rotation (<90°) at release is favorable. All three groups release the ball while still in external rotation meaning that their shoulder is still behind their torso at release. The sidearm group has the most external rotation at release and could be due to the arm
lagging more behind the torso during torso transverse acceleration. This is due to the arm coming more around the body into release, as compared to a more over the top method seen in more vertical arm slots.

To minimize torque on the elbow it is important to try to keep the elbow flexion angle to 90° until after max external rotation [8]. Table 14 shows that the overhand group is the best at maintaining this angle, and that as the arm slot drops so does the angle of elbow flexion. This could be explained by the rotational nature of sidearm pitchers. Since sidearm pitchers are more rotational, they could create higher centripetal forces, and if the pitcher has their arm outside of 90° once the trunk started rotating the centripetal force would cause the forearm to flyout and thus increase extension going into max external rotation. If the pitcher had their elbow inside of 90° at the start of trunk acceleration than the centripetal force would keep the elbow closer to the body.

6.4.1.6 Hip-Shoulder Separation

The overhand group has the most forward tilt hip-shoulder separation, which could be the reason for it having the largest maximum sagittal torso angular velocity. Having hip-shoulder separation in any plane creates tension that can be used to store and transfer energy to other segments. Having forward tilt separation allows for sagittal torso angular velocity to be created.

The more vertical arm slot groups will also have larger lateral hip-shoulder separation due to the larger torso lateral tilts that are characteristic of their arm slot.

Rotational hip-shoulder separation or hip-shoulder separation in the transverse plane is used to create transverse torso angular velocity, and it one of the keys of efficient pitching mechanics. Not only is being able to create hip-shoulder separation important
but being able to close the gap or get to $0^\circ$ of separation by release is even more important. Hip-shoulder separation at max external rotation provides insight into how well a pitcher is closing the gap. It can be seen in Table 15 that the sidearm group does the best job of being able to start closing the gap quickly after foot plant. As the arm slot goes up the pitcher has more separation at max external rotation. If the pitcher is unable to close the gap by release, then they are not maximizing their energy transfer.

**6.4.2 Correlations to Velocity**

For each arm slot group, we examined the correlation coefficients for the complete list of metrics. The five highest correlations for each group can be found in Table 16-18. Here we are looking to determine not only what metrics correlate highly to ball velocity for each group, but also what plane of motion does that metric occur. The results of the overhand group were all significant with three of the five metrics being of the sagittal plane. The metric with the highest correlation to ball velocity was maximum elbow sagittal angular velocity ($r = 0.726$). This is how quickly a pitcher can extend their elbow into ball release and has been found in other studies to be highly correlated to ball velocity [27]. The three-quarter arm slot group had 4 of its 5 highest correlations come from the sagittal plane with its highest correlation being pelvic anterior tilt at release ($r = 0.652$). As discussed in **3.4.2.2 Pelvic Forward Tilt**, pelvic anterior tilt is thought to enable shoulder external rotation and t-spine extension going from max external rotation into release. This would aid in ball velocity by facilitating the upper body into getting into optimal positions for energy transfer. The sidearm group had many of its highest correlation metrics come from the frontal plane, but due to the small sample size of this group none of the correlations were significant.
6.4.3 Planar Correlations to Velocity

6.4.3.1 MLR

Multiple linear regression of the maximum angular velocities for each of the five main segments in each plane determined that ball velocity for overhand throwers was mostly due to frontal kinematics with the influence of the pelvis, torso, and hand all being in the frontal plane. This equation relied heavily on the frontal plane had a correlation coefficient of 0.694 with ball velocity, which is lower than some of the individual metric correlations. This means that for correlations to velocity single kinematic metrics may provide more insight than a combination of these metrics. MLR also showed that for the three-quarter slot pitchers the magnitude of a 5-segment kinematic sequence that had the highest correlation to ball velocity was a combination of all three planes with the sagittal plane having the smallest representation. This had a correlation coefficient to ball velocity of 0.544. These results may suggest that more research should be done examining frontal plane kinematics, and its contribution to ball velocity. Again, the kinematic MLR was not found for the sidearm group due to the small sample size resulting in a high number of equations having a correlation coefficient of 1.

To better determine the dominant plane of motion for each arm slot we grouped ten commonly identified and studied anatomical metrics by plane. Then we found the MLR correlation to ball velocity for each planar grouping at various time points throughout the pitching motion, and overall. The overhand pitching group starts out more reliant on the transverse plane as seen as its greatest correlation at foot plant occurring in the transverse plane, but then transitions to the sagittal plane during max external rotation and release. Combining all the time points the overhand group had very similar
correlations between the sagittal \( r = 0.646 \) and transverse planes \( r = 0.658 \) meaning that both contribute to velocity, but at max external rotation and release where the mechanics begin to adjust more for arm slot the sagittal plane is dominant. The three-quarter arm slot pitchers had the highest overall correlation to the sagittal plane metrics \( r = 0.670 \), but still had good representation of both the sagittal and the transverse plane at release. Due to the small sample size of sidearm pitchers all three planes had high correlations to velocity overall. It can be seen though in Figure 37 that the sidearm pitchers exhibit the reverse trend of the overhand pitchers. Although all the correlations are very close in value these pitchers do exhibit the highest correlation at foot plant to the sagittal plane, and the highest correlation at release to the transverse plane. This means that sidearm pitchers become more transverse plane dominant throughout their motion. The transverse plane equates to rotational energy generation, while the sagittal plane is more linear. This means that arm slot influences energy generation and transfer strategies of pitchers with the overhand group starting more rotational and transitioning too linear, and the sidearm group following the opposite trend.

### 6.4.3.1 Dominant Plane of Motion

Examining the information from the velocity correlations studies it appears that the dominant plane of motion for the overhand group is the sagittal plane. This is because 60% of its top five highest correlations to velocity were in the sagittal plane. The sagittal plane for overhand pitchers also had almost the same overall planar correlation to velocity as the transverse plane anatomical metrics but had the highest correlation at max external rotation and release. The three-quarter arm slot pitchers also had the sagittal
plane as their dominant plane of motion with it accounting for 80% of its five highest correlations, and it being the highest correlation in terms of anatomical metrics both overall and at release. The sidearm pitchers on the other hand exhibited opposite trends as the other two arm slot groups and as such are transverse plane dominant. This can be seen in their 2 out of their 5 highest correlations coming in the transverse plane, and the transverse plane having the highest correlation to velocity both at max external rotation and release. These dominant planes of motion appear to agree with the corresponding pitching mechanics of each group. The more vertical the arm slot the more a pitcher relies on the sagittal plane, and the more horizontal the arm slot the more a pitcher relies on the transverse plane to generate velocity.

### 6.5 Limitations and Future Direction

One limitation to this study is the sample size of pitchers for each group. The groups did not have equal sample sizes with the sidearm group only having 7 pitchers. In the future we would like to repeat the study with an increased number of sidearm pitchers to get a better idea of their mechanics and their differences from the other arm slot groupings. Increasing the sample size of each group also provides a better representation of the population means.

### 6.6 Conclusion

Overhand and three-quarter arm slot pitchers follow very similar movement patterns. Arm slot affects dominant plane, and as such the strategy for energy generation. Overhand pitchers start rotational and transition to linear energy for release, while the
sidearm pitchers exhibit the opposite trend. Three-quarter arm slot pitchers don’t follow either of these trends using a combination of the sagittal and transverse plane from foot plant to release.

**Chapter 7: Study 5 – Differences attributed to mobility**

**7.1 Background**

**7.1.1 Mobility Background**

A pitcher’s mobility determines how and why they display certain movement patterns and has been thought to be related to pitcher injury. The repetitiveness of the pitching motion when combined with the length of a baseball season can cause physiological adaptations in muscles and joint range of motion [72,73]. One factor that can limit range of motion (ROM) is muscle tightness, which is characterized by an increase in tension on the muscle that limits the muscles length and ability to stretch [74]. Due to these adaptations pitcher mobility has been studied for its relationship to injury.

One method for assessing changes in ROM is to perform a static mobility assessment to compare differences between throwing side and non-throwing side range of motion [75]. Another method, which has been used to assess elbow and shoulder injuries compares the ROM of injured players to non-injured players, which found that injured players had greater shoulder internal range of motion than non-injured players [72]. Other studies have examined hip range of motion and its influence on shoulder abduction within the pitching motion and found that hip rotational range of motion did have a significant relationship to both shoulder external rotation torque and horizontal adduction range of motion [76]. This research shows the intricacies that connect the lower and
upper body. All these studies looked to examine direct relationships to injury, we look to examine the influence of mobility on pitching postural metrics, kinematics, and kinetics. This would provide a better picture of why pitchers with specific mobility issues experience certain movement patterns.

7.1.2 Included Assessments Backgrounds

7.1.2.1 Tight Neck Flexor Muscles

The neck flexor muscles are a group of four muscles that control flexion of the neck. Pitchers with limited neck mobility during preseason have an increased risk of missing playing time due to shoulder and elbow injuries [77]. There are anatomical relationships between the neck, spine, and upper extremities that make the neck a potential factor in upper extremity injuries [78]. Other than anatomical relationships the neck is also important for pitching accuracy and gaze stabilization.

7.1.2.2 Insufficient Serratus Strength

The serratus anterior is a muscle that is also involved in scapular positioning. This muscle is important in stabilizing the shoulder joint from arm cocking to deceleration [19]. As such the serratus muscle needs to combat high shoulder forces and must have adequate strength to do so. Sufficient strength and usage of the serratus muscle may come with training and experience as there are differences in muscle activation between professional and amateur pitchers. Professional pitchers have more serratus anterior activation during the acceleration phase, while amateur pitchers have increased activation during the late cocking phase [79]. Having sufficient serratus strength allows for shoulder
stability thus promoting better mechanics during the acceleration phase, and decreased risk of injury.

7.1.2.3 Tight Pectoralis Minor

Pectoralis minor (pec minor) is a muscle that connects the scapula to the anterior thorax and is involved in scapular positioning. Since the pitching motion involves repetitive protraction and downward rotation of the scapula the pec minor can become tight or even go through adaptive shortening [80]. This adaptive shortening has been associated with shoulder pain and injury in athletes. Along with scapular positioning it has been found that amateur pitchers have a more active pec minor during the acceleration phase as compared to professional pitchers that rely more on their latissimus dorsi [19]. This implies that a tight pec minor may have implications on acceleration phase metrics of the arm and may be more prominent in amateur pitchers.

7.1.2.4 Tight Latissimus Dorsi

The latissimus dorsi (lats) muscle connects the torso to the humerus, and has various functions including humerus internal rotation, horizontal abduction, adduction, and secondary roles in torso mobility. The roles of the lats especially for internal rotation and horizontal abduction make them vital to the pitching motion in terms of both pitch velocity and risk of injury. As the pitcher enters max external rotation the lats eccentrically contract to stop the shoulder from going too far into external rotation, protecting the shoulder joint [81]. Transitioning into the acceleration phase the lats concentrically contract to internally rotate the arm at speeds up to 7000°/s [82]. Sport
specific lat tightness or length adaptations could have implications on upper extremity postural metrics, kinematics, and kinetics.

7.1.2.5 Insufficient Thoracic Spine Extension

The torso is an important source of energy generation and transfer during the pitching motion. Appropriate mobility of the spine especially in the transverse and sagittal planes is crucial for optimal pitching mechanics [83]. As discussed in 3.4.1.3 Sagittal Plane Kinematics thoracic extension increases scapular posterior tilting, external rotation, and maximum shoulder external rotation [31]. Having limited thoracic spine (T-spine) extension could thus have upstream mechanical affects on the pitching motion.

7.1.2.6 Tight Adductors

The adductor muscles are a group of muscles that connect the hip to the thigh and are responsible for hip adduction, flexion, and rotation. Hip range of motion and strength has been shown to decrease in collegiate pitchers from preseason to postseason [73]. Being able to maintain hip ROM throughout the season is important as hip abduction and adduction range of motion are correlated to pitching metrics such as pitch velocity, hip-shoulder separation, and stride length [84].
7.2 Methods

7.2.1 Mobility Testing

54 of the 62 pitchers who received mocaps also completed mobility assessments at the baseball training facility. These mobility assessments included range of motion tests, mobility, tightness, breathing, and strength assessments. The results were not quantitative but were binary with either a pitcher being categorized as yes or no for each assessment category. For example, one assessment was for a tight pectoral major muscle, so the result of the assessment would either be yes, they have a tight pec major or no they do not.

7.2.2 Statistical Analysis

Pitchers were then grouped by their outcome for each test as being either deficient or sufficient in that assessment. A pitcher was deficient in their assessment if they were labelled as having limited mobility, tightness, insufficient strength, or insufficient stability. A pitcher was sufficient in their assessment if they fell within a normal range for that assessment. The groups were then compared using a two-sample t-test with unequal variance, and \( \alpha = 0.05 \). The groups were assessed for all the metrics listed in Appendix 2.2, but only the metrics with significant differences between the groups are listed in the results section.

7.2.3 Excluded Assessments

Sample sizes per group were chosen based on a sample size calculation with an effect size of 0.8 (Figure 38). This effect size is based on the difference between group
means and is used to ensure that there are at least 0.8 standard deviations between the population means. The value of 0.8 was chosen at it is the first value that constitutes a large effect, or large difference between the two groups [85]. The results determined that each group needed at least 19 subjects. Any mobility assessments that did not have at least 19 pitchers per group was removed from the study. Mobility assessments were excluded from the results if no significant difference was found across subject groupings. A list of the mobility assessments displayed in the results section can be seen in Table 19.

\[
\begin{align*}
    n &= 2 \left( \frac{z_{1-\alpha} + z_{1-\beta}}{\delta} \right)^2 \quad (7) \\
    n &= 2 \left( \frac{t_{1-\alpha} + t_{1-\beta}}{\delta} \right)^2 \quad (8)
\end{align*}
\]

**Figure 38:** Sample size calculation equations using effect size. Here \( \alpha = 0.05 \), \( \beta = 0.2 \), and \( \delta = 0.8 \). Equation 4 is used first followed by equation 5 if \( n < 30 \) to iterate to a sample size.

**Table 19:** Included Mobility Assessments

<table>
<thead>
<tr>
<th>Included Mobility Assessments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight Pec Minor</td>
</tr>
<tr>
<td>Tight Neck Flexor</td>
</tr>
<tr>
<td>Insufficient T-spine Extension</td>
</tr>
<tr>
<td>Insufficient Serratus Strength</td>
</tr>
<tr>
<td>Tight Adductors</td>
</tr>
<tr>
<td>Tight Lats</td>
</tr>
</tbody>
</table>
7.3 Results

Table 20: Tight Neck Flexor Potential Implications

<table>
<thead>
<tr>
<th>Mobility Parameter</th>
<th>Deficient Sample Size</th>
<th>Sufficient Sample Size</th>
<th>Comparison Metric</th>
<th>Deficient Mean</th>
<th>Sufficient Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight Neck Flexors</td>
<td>19</td>
<td>35</td>
<td>Maximum Frontal Pelvis Angular Velocity*&lt;sub&gt;C&lt;/sub&gt;</td>
<td>317.4°/s</td>
<td>366.6°/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pelvis Rotation Angle at Foot Plant*&lt;sub&gt;C&lt;/sub&gt;</td>
<td>42.61°</td>
<td>50.55°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum Lead Knee Sagittal Angular Velocity*&lt;sub&gt;A&lt;/sub&gt;</td>
<td>223.3°/s</td>
<td>313.3°/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lead Knee Valgus Angle at Foot Plant*&lt;sub&gt;A&lt;/sub&gt;</td>
<td>5.717°</td>
<td>2.488°</td>
</tr>
</tbody>
</table>

* = p < 0.05  
** = p < 0.01  
*** = p < 0.001 

A = Sufficient population has a better outcome  
B = Deficient population has a better outcome  
C = Unknown conclusion

There were 19 pitchers with tight neck flexor muscles, and 35 pitchers without tight neck flexors. There were two kinematic, two kinetic, and two postural metric significant differences between these groups. In terms of kinematics pitchers with a tight neck flexor had lower angular velocities of both the frontal pelvis velocity and lead knee sagittal velocity. The important finding here is that the group with the tight neck flexors exhibited a 90°/s drop in lead knee sagittal angular velocity. In terms of postural metrics, the tight neck flexor group had 8° less of pelvis rotation, and 3° more knee valgus at foot plant.
Table 21: Insufficient Serratus Strength Potential Implications

<table>
<thead>
<tr>
<th>Mobility Parameter</th>
<th>Deficient Sample Size</th>
<th>Sufficient Sample Size</th>
<th>Comparison Group</th>
<th>Deficient Mean</th>
<th>Sufficient Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insufficient Serratus Strength</td>
<td>21</td>
<td>33</td>
<td></td>
<td>Maximum Elbow Sagittal Angular Velocity* A</td>
<td>2200°/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lead Knee Sagittal Angular Velocity at Release** A</td>
<td>228.5°/s</td>
</tr>
</tbody>
</table>

* = p < 0.05  
** = p < 0.01  
*** = p < 0.001  
A = Sufficient population has a better outcome  
B = Deficient population has a better outcome  
C = Unknown conclusion

Pitchers with insufficient serratus strength have decreased angular velocities of both the sagittal lead knee and sagittal elbow. The elbow sagittal angular velocity in the deficient group is 2200°/s as compared to 2412°/s for the sufficient group. The lead knee extension velocity is 86.9°/s lower in the deficient group.
There were 30 pitchers classified as having tight pec minor on their throwing side (deficient), and 24 pitchers classified as not having a tight pec minor (sufficient). Comparing the two groups found significant differences in four pitching metrics. Half of the metrics showed favorable results for the deficient group, one had an unknown conclusion, and one was favorable for the sufficient group. There was a significant difference between the two groups in terms of maximum frontal elbow angular velocity with the deficient group having a velocity 200°/s greater than the sufficient group. This trend continued through the other kinematic differences as the deficient group also showed greater angular velocities for maximum elbow sagittal angular velocity and maximum transverse shoulder angular velocity.
Table 23: Tight Lats Potential Implications

<table>
<thead>
<tr>
<th>Mobility Parameter</th>
<th>Deficient Sample Size</th>
<th>Sufficient Sample Size</th>
<th>Comparison Metric</th>
<th>Deficient Mean</th>
<th>Sufficient Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight* C</td>
<td></td>
<td></td>
<td></td>
<td>179.7lbs</td>
<td>197.7lbs</td>
</tr>
<tr>
<td>Trunk Lateral Tilt Angle at Foot Plant* C</td>
<td></td>
<td></td>
<td></td>
<td>11.61°</td>
<td>5.396°</td>
</tr>
<tr>
<td>Maximum Hand Sagittal Angular Velocity* C</td>
<td></td>
<td></td>
<td></td>
<td>4972°/s</td>
<td>4009°/s</td>
</tr>
<tr>
<td>Pitching Elbow Flexion Angle at Release* C</td>
<td></td>
<td></td>
<td></td>
<td>19.39°</td>
<td>23.84°</td>
</tr>
<tr>
<td>Pitching Shoulder Abduction Angle at Max External Rotation* B</td>
<td>27</td>
<td>27</td>
<td></td>
<td>93.32°</td>
<td>97.66°</td>
</tr>
<tr>
<td>Pitching Shoulder External Rotation Angle at Max External Rotation* A</td>
<td></td>
<td></td>
<td></td>
<td>154.5°</td>
<td>162.8°</td>
</tr>
<tr>
<td>Maximum Elbow Flexion Torque Before Release* A</td>
<td></td>
<td></td>
<td></td>
<td>0.047</td>
<td>0.018</td>
</tr>
<tr>
<td>Maximum Elbow Varus Torque Before Release* A</td>
<td></td>
<td></td>
<td></td>
<td>0.097</td>
<td>0.059</td>
</tr>
<tr>
<td>Maximum Shoulder Horizontal Adduction Torque Before Release* A</td>
<td></td>
<td></td>
<td></td>
<td>-0.161</td>
<td>-0.096</td>
</tr>
<tr>
<td>Maximum Shoulder Abduction Torque Before Release* A</td>
<td></td>
<td></td>
<td></td>
<td>-0.089</td>
<td>-0.038</td>
</tr>
</tbody>
</table>

* = p < 0.05
** = p < 0.01
*** = p < 0.001
A = Sufficient population has a better outcome
B = Deficient population has a better outcome
C = Unknown conclusion

Half of the subjects tested experienced lat tightness resulting in significant differences in eight metrics when compared to subjects without tightness. All metrics that were significantly different between the groups were for the upper extremities apart from weight, where the lat tightness group was 18lbs lighter than the sufficient group. The deficient group also experienced more trunk lateral tilt at foot plant, increased hand sagittal angular velocity, and less elbow flexion at release. Since the lat plays a part in adduction and shoulder rotation it makes sense that both metrics were affected by tight lats. The pitchers with tight lats have decreased shoulder abduction at MER, but with a population average of 93.32° this gives an advantage to the deficient group as they are closer to maintaining that optimal 90° of abduction throughout the throwing motion. The deficient group also has decreased maximum external rotation with a value of 154.5° as compared to 162.8° for the sufficient group. Tight lat pitchers also experience higher kinetics for four different torque values, which included an elbow varus torque that was 164% higher than the sufficient group.
7.3.5 Insufficient T-Spine Extension

Table 24: Insufficient T-spine Extension Potential Implications

<table>
<thead>
<tr>
<th>Mobility Parameter</th>
<th>Deficient Sample Size</th>
<th>Sufficient Sample Size</th>
<th>Comparison Metric</th>
<th>Deficient Mean</th>
<th>Sufficient Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insufficient T-spine Extension</td>
<td>23</td>
<td>31</td>
<td>Pitching Elbow Flexion Angle at Foot Plant*</td>
<td>88.27°</td>
<td>97.92°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pelvis Flexion Angle at Foot Plant*</td>
<td>9.123°</td>
<td>14.17°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum Shoulder Abduction Torque After Release</td>
<td>-0.055</td>
<td>-0.101</td>
</tr>
</tbody>
</table>

* = p < 0.05  
** = p < 0.01  
*** = p < 0.001  
A = Sufficient population has a better outcome  
B = Deficient population has a better outcome  
C = Unknown conclusion

The 23 pitchers with insufficient T-spine extension had better metrics than their counterparts with normal T-spine extension. The deficient pitchers had an elbow flexion angle closer to 90° at foot plant, a lower pelvis flexion angle at foot plant at 9°, and a lower shoulder abduction torque after release, which was 45.5% lower than the sufficient group.
Table 25: Tight Adductors Potential Implications

<table>
<thead>
<tr>
<th>Mobility Parameter</th>
<th>Deficient Sample Size</th>
<th>Sufficient Sample Size</th>
<th>Comparison Metric</th>
<th>Deficient Mean</th>
<th>Sufficient Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight Adductors</td>
<td>27</td>
<td>27</td>
<td>Maximum Torso</td>
<td>1126°/s</td>
<td>1052°/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Transverse Angular Velocity***B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* = p < 0.05  
** = p < 0.01  
*** = p < 0.001  
A = Sufficient population has a better outcome  
B = Deficient population has a better outcome  
C = Unknown conclusion

There were an equal number of pitchers with and without tight adductors. These groups only had significant differences in their maximum torso transverse angular velocity. The kinematic parameter of torso angular velocity was higher in the group with tight adductors with a velocity of 1126°/s as compared to 1052°/s in the group without tight adductors.

7.4 Discussion

7.4.1 Tight Neck Flexor

Surprisingly most of the differences between the neck flexor groups involved the lower extremities of the pelvis and knee. Pelvis frontal angular velocity was found in 3.3 Results to be correlated to pitch velocity putting the sufficient group at a pitch velocity advantage since they have a higher angular velocity. Another metric that has been found to be correlated with pitch velocity and gives the sufficient group an advantage is the knee sagittal angular velocity. Knee sagittal or extension angular velocity is higher in
high velocity pitchers as compared to low velocity pitchers [56]. These two metrics make a case that proper neck mobility can help pitchers to increase their pitch velocity through lower extremity kinematic metrics. The knee valgus angle at foot plant has injury implications as landing with a larger valgus angle increases the angular impulse at the knee increasing risk of injury [60]. Neck mobility limitations could increase the likelihood of knee injuries along with previously discovered implications for shoulder and elbow injuries in pitchers [77]. This puts pitchers with neck mobility at an increased risk of injury for both upper and lower extremities.

7.4.2 Insufficient Serratus Strength

Increased serratus activation during the acceleration phase of the pitching motion is seen in professional pitchers [75]. Elbow extension angular velocity is the kinematic metric with the highest correlation to velocity during the acceleration phase and is greater in pitchers with adequate serratus strength. The findings in this study support the idea that proper use of the serratus during the acceleration phase allows for more optimal pitching mechanics. Pitchers with sufficient serratus strength were also found to have increased knee extension angular velocity, which is another metric related to pitch velocity [56]. This combination of metrics gives pitchers within the sufficient group an advantage in terms of pitch velocity, since having higher metrics are related to increases in pitching velocity.
7.4.3 Tight Pec Minor

Pitchers that have a tight pec minor have a higher elbow frontal or varus angular velocity. Elbow frontal angular velocity is not a commonly researched metric, but from 3.3 Results and 4.3.2 Maximum Elbow Varus Torque Before Release it has been shown to have no correlation to elbow varus torque or pitch velocity. Thus, it is unknown if having a higher or lower elbow frontal velocity is beneficial for a pitcher. The metric that is correlated to pitch velocity though is the maximum sagittal elbow angular velocity, which is also higher in the deficient or tight group. This group also has a higher transverse shoulder angular velocity, which has a correlation of 0.252 to pitch velocity. Both these metrics are better for the deficient group, which requires additional research to determine the cause of this finding.

7.4.4 Tight Lats

The lats play multiple major roles throughout the pitching motion thus making their mobility a high priority for pitchers. The tight lat pitchers were found to have a significant increase in maximum hand sagittal angular velocity, which was found earlier in Study 2 – Torque Correlations and Averages to have correlations to all three torque metrics examined. Maximum elbow varus torque was also found to be significantly higher in the tight lat group and may be a result of the increase in hand sagittal velocity. Being able to manipulate and manage hand sagittal angular velocity might be key to decreasing shoulder and elbow torque in pitchers, especially pitchers that experience lat tightness.
Lat tightness may be beneficial for shoulder abduction in pitchers as decreasing lat stretch limits shoulder abduction, which for the pitchers in this study allowed them to have a better angle at MER. Maximum shoulder external rotation has a correlation of 0.465 to pitch velocity (3.3 Results) making it an important metric for pitch velocity. Since the lat eccentrically contracts to regulate max external rotation having a tight lat would motion limit the amount of external rotation a pitcher can achieve. This explains why pitchers with a tight lat have an 8.3° decrease in their maximum external rotation angle, which may have implications on pitch velocity. The latissimus dorsi muscle exhibits sport specific adaptions in length, which need to be managed to maintain the physical demands of the sport [86]. As a result, lat mobility must be emphasized for pitchers as it can affect pitch velocity and both shoulder and elbow kinetics.

7.4.5 Insufficient T-spine Extension

Based on the anatomical connections between thoracic extension and the arm we expected to find group differences related to shoulder metrics, and more specifically maximum shoulder external rotation. There were no significant differences between groups in terms of most shoulder metrics. Pitchers with insufficient T-spine extension did present lower shoulder abduction torque after release, but with no other shoulder metric differences the cause of this reduction in torque is unknown. Pitchers with insufficient T-spine extension do a better job of maintaining an elbow flexion angle around 90° at foot plant and have a lower pelvis flexion angle at foot plant. A lower pelvis flexion angle at foot plant could represent holding a posterior tilt and hinge longer during the stride phase.
Proper hip hinge helps to stabilize the spine and engage the hamstring and gluteus maximus muscles [68,87].

7.4.6 Tight Adductors

Hip mobility has been previously shown to have implications for injury where decreased hip mobility resulted in an increase in shoulder external rotation torque and risk of injury [76,88]. It is thought that limited hip mobility can restrict the energy generation and transfer from the lower extremities to the upper extremities during the pitching motion. This reduction in available energy may cause pitchers to compensate by using more of their upper body for force generation and in turn increasing the stress on their arm [76]. We did not duplicate these findings within our study, but instead found that the deficient group was able to generate higher torso rotational velocity. This could be a result of a more efficient transfer of energy from the hips, or increased energy generation from the torso. The lower angular velocity seen in the sufficient group may put them at an increased risk of injury as their potential for energy transfer from the torso to the arm is limited, which could lead to compensations with the arm and an increase in stress on the elbow [19,89]. Additional analysis is needed to examine the potential difference in energy flow between these two groups to provide a better understanding of how tight adductors affects kinematics.

7.5 Limitations and Future Direction

This study was limited by the total sample size and the sample size of pitchers in each grouping (deficient and sufficient). Many mobility assessments were not examined,
or the results thrown out due to the large difference in sample size between the two groups. Ideally in the future a larger study would be conducted with increased sample size, allowing for groups that better represent the population and allow for examination of more mobility assessments.

Additionally, an expansion study should be conducted to further investigate the causation of findings in this study. For example, the tight neck flexor results found significant differences in lower extremity metrics. Further research thus is needed to determine the influence of neck flexors on the lower extremities or how tight neck flexor movement patterns influences the lower extremities.

7.6 Conclusion

Pitcher mobility has implications for both pitch velocity and risk of injury. In this study six muscle limitations were examined for differences between a deficient and sufficient group in terms of mobility and strength. There were postural, kinematic, and kinetic differences between the groups. Significant decreases in metrics that are correlated to velocity were found in groups experiencing tight neck flexors, insufficient serratus strength, and tight lats. Significant increases in shoulder and elbow torques were also displayed by the tight lat group. These results raise the importance of mobility training for pitchers as a method to maintain pitch velocity and combat increases in torque throughout the season.
Part 2: Summary

Part 2 looked to examine if anatomical factors affected postural metrics and kinematics. The anatomical factors examined were height, weight, age, segment lengths, arm slot, and mobility. Height, weight, age, and segment length correlations did not provide many important findings. Weight was found to be correlated to pitch velocity but needs further research into body composition for practical applications. Height and trunk length were both found to be correlated to arm slot with taller pitchers and pitchers with longer torsos both exhibiting a more horizontal arm slot.

Arm slot statistical analysis provided more insight into how pitchers generate energy with different arm slots. It was found that pitchers with a more vertical arm slot relied more on the sagittal plane, whereas pitchers with a more horizontal arm slot relied more on the transverse plane. This has important implications for coaching as each arm slot needs to be able to move more efficiently in its respective plane of motion.

Examining mobility and its relationship to pitching mechanics provided information on how mobility limitations can affect different postural and kinematic metrics and indirectly affect pitch velocity and torque values. Tight lats appears to have the most influence on pitching mechanics as pitchers with tight lats had a reduction in multiple metrics that were correlated to pitch velocity, and higher kinetic variables. This promotes the importance of pitcher mobility throughout the season for both pitch velocity and pitcher health.
Chapter 8: Overall Conclusion

These studies expanded the research area on postural and kinematic metrics that correlate to pitch velocity and torque values, while also investigating various anatomical factors that influence these postural and kinematic metrics. Increasing pitch velocity may come with an associated increase in torque, but by manipulating pitching mechanics we can increase efficiency thus maintaining velocity while also decreasing torque. Grouping metrics into individual, tradeoff, positive, and negative based on their correlations allows coaches to focus on metrics that directly impact pitch velocity, torque, or both. Using the information in Tables 8 and 9 coaches know which metric to manipulate to get an increase in velocity, a decrease in torque, and which metrics have an effect on both. It is important to understand these correlations and their implications as simply increasing pelvis forward tilt would increase pitch velocity, but it comes at the expense of also increasing torque. With this knowledge coaches can better examine the tradeoffs and risks of each metric before implementing them into their pitching programs.

Determining anatomical factors that influence postural and kinematic metrics provides information on pitcher limitations, advantages, and areas of individualization. Taller pitchers typically have a more horizontal arm slot, which may be a result of the way their body self organizes and more efficiently generates energy. As a result, experimenting with a lower arm slot for a taller pitcher may help them generate more energy, increase pitch velocity, and feel more comfortable pitching. These taller pitchers may move better in the transverse plane, which makes them more inclined to adopt a more horizontal arm slot. Each arm slot group moves differently, and it was found that more vertical arm slots favor the sagittal plane as horizontal arm slots favor the transverse
plane. This information allows coaches to focus more heavily on the plane of motion that dominates a pitcher’s mechanics.

Mobility plays an important role in athletics but is prone to sport specific adaptations. These adaptations may decrease mobility, which can affect pitching mechanics, pitch velocity, and torque. It was found that limited mobility restricted some postural metrics and kinematics, while also increasing torque values. Knowing the anatomical causes behind pitching postural metrics allows coaches to help fix the cause of the problem. For example, a pitcher experiencing a low maximum shoulder external rotation angle may have a tight lat that needs to be addressed to gain more external rotation. Without knowing that a tight lat is a possible cause the pitcher will be unable to gain external rotation, which can limit their pitch velocity.

The findings laid out here provide a map for coaches and practitioners to better understand the connections between anatomy, pitching mechanics, pitch velocity, and risk of injury. This allows for a more individualized pitching development program, which can train pitchers to increase their velocity while decreasing their risk of injury. The ideas and methods implemented here can be expanded to other sports, especially overhead or rotational sports that involve similar movement patterns. A deeper understanding of anatomical influence on mechanics is key to individualized training and development across sports. The goal of this research is to help athletes optimize their movement patterns for maximal sport performance, and minimal risk of injury.
Summary

Two of the keys to a baseball pitcher’s success are their pitch velocity and their ability to stay on the field by minimizing their risk of injury. The dynamic and high velocity mechanics of the pitching motion create large torques that make pitchers highly susceptible to injury. As such it is important for pitcher’s to be able to increase or maintain their pitch velocity, while decreasing their torque values. The top 5 metrics found to be correlated to pitch velocity can be seen in the table below. These are metrics that coaches should focus on increasing to generate a corresponding increase in pitch velocity.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvic Forward Tilt at MER and Release</td>
<td>Shoulder External Rotation at MER</td>
</tr>
<tr>
<td></td>
<td>Knee Extension at MER</td>
</tr>
<tr>
<td>Maximum Pelvis Sagittal Angular Velocity</td>
<td>Maximum Elbow Sagittal Angular Velocity</td>
</tr>
</tbody>
</table>

To ensure that torque doesn’t increase with velocity it is equally important for coaches to focus on decreasing metrics correlated to torque values.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Hand Sagittal Angular Velocity</td>
<td>Maximum Hand Frontal Angular Velocity</td>
</tr>
<tr>
<td>Maximum Hand Transverse Angular Velocity</td>
<td>Pelvic Forward Tilt at MER and Release</td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction at Foot Plant</td>
<td></td>
</tr>
</tbody>
</table>

Pitch velocity and torque are affected by both a pitcher’s mechanics and their anatomy. Increasing pitcher weight and age are associated with an increase in pitch velocity, while pitcher height and trunk length are related to arm slot. Taller pitchers generally have a more horizontal arm slot, meaning they use more transverse plane movements to generate their pitch velocity. A more vertical arm slot on the other hand is
associated with the sagittal plane having the highest contribution to pitch velocity. These differences are depicted in the postural and kinematic preferences of pitchers with each arm slot.

Pitcher mobility is an additional factor that needs to be taken into consideration when assessing pitching mechanics. Here it was determined that pitchers with tight neck flexors, insufficient serratus strength, and tight lats had decreases in metrics correlated to pitch velocity thus putting them at a velocity disadvantage. Additionally, pitchers with tight lats also demonstrated an increase not only in metrics associated with an increase in torque, but the torque values themselves as well. This raises the importance of mobility training for pitchers as a method to maintain their pitch velocity and combat increases in torque throughout the season. These findings provide a better understanding of the connections between anatomy, pitching mechanics, pitch velocity, and risk of injury. Coaches can use these results to better develop their pitchers.
Appendix 1: References


Appendix 2: Additional Figures and Tables

Appendix 2.1 Mocap Marker Placement

Marker placement for Mocap analysis used in the data collection process. *Figures taken from Qualisys PAF Baseball MAC Marker Set, 2020 (Qualisys) [90].*
### Appendix 2.2 Complete List of Metrics Examined in this Study

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
<th>Planes and Sign Convention</th>
</tr>
</thead>
</table>
| Back Ankle Angle and Angular Velocity       | Back virtual foot with respect to (wrt) the back shank | X: Dorsiflexion = +  
Y: Inversion = +  
Z: Internal Rotation = + |
| Back Foot Angle                             | Back foot wrt the lab axes                      | X: Out = +  
Y: Out = +  
Z:                                                   |
| Back Foot COG                               | Back foot COG position                          | X: Right of the Lab Axis = +  
Y: Towards home plate = +  
Z: Upward = + |
| Back Hip Angle and Angular Velocity         | Back thigh wrt the pelvis                       | X: Flexion = +  
Y: Adduction = +  
Z: Internal Rotation = + |
| Back Knee Angle and Angular Velocity        | Back shank wrt the back thigh                   | X: Flexion = +  
Y: Varus = +  
Z: Internal Rotation = + |
| Elbow Force                                 | Elbow force normalized to BW                    | X: Flexion = +  
Y: Varus = +  
Z: Pronation = + |
| Elbow Torque                                | Elbow torque normalized to BW*Height             | X: Flexion = +  
Y: Varus = +  
Z: Pronation = + |
| Glove Elbow Angle                           | Glove upper arm wrt the glove lower arm         | X: Flexion = +  
Y: Varus = +  
Z: Pronation = + |
| Glove Shoulder Angle and Angular Velocity   | Glove upper arm wrt the thorax                  | X: Horizontal Adduction = +  
Y: Abduction = +  
Z: External Rotation = + |
| Head Angle and Angular Velocity             | Head wrt the virtual lab                        | X: Flexion = +  
Y: Glove side tilt = + |
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>X:</th>
<th>Y:</th>
<th>Z:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip-Shoulder Separation</td>
<td>Thorax wrt the pelvis</td>
<td>±</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: More pelvic flexion than trunk flexion = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: More pelvic tilt than trunk rotation toward the glove side = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: = More pelvic rotation than trunk rotation toward the glove side+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead Ankle Angle and Angular Velocity</td>
<td>Lead virtual foot wrt the lead shank</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Dorsiflexion = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Inversion = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Internal Rotation = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead Hip Angular Velocity</td>
<td>Lead thigh wrt the pelvis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Flexion = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Adduction = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Internal Rotation = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead Knee Angle and Angular Velocity</td>
<td>Lead shank wrt the lead thigh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Flexion = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Varus = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Internal Rotation = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis Angle and Angular Velocity</td>
<td>Pelvis wrt the virtual lab</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Flexion = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Lateral tilt towards the glove side = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Rotation toward the glove side = + (0° is square to home plate)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis COG and COG Velocity</td>
<td>Pelvis COG position</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Right of the Lab Axis = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Towards home plate = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Upward = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitching Elbow Angle and Angular Velocity</td>
<td>Pitching upper arm wrt the pitching lower arm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Flexion = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Varus = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Pronation = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitching Hand Angle and Angular Velocity</td>
<td>Angle created by the pitching lower arm wrt the pitching hand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Flexion = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Ulnar deviation = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Pronation = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitching Shoulder Angle and Angular Velocity</td>
<td>Angle created by the pitching upper arm wrt the thorax</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Horizontal Adduction = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Abduction = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: External Rotation = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder Force</td>
<td>Shoulder force normalized to BW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Horizontal Abduction = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Adduction = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Internal Rotation = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder Torque</td>
<td>Shoulder Torque normalized to BW*Height</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Horizontal Abduction = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Adduction = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Internal Rotation = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Angle and Angular Velocity</td>
<td>Angle created by the thorax wrt the virtual lab</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X: Flexion = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y: Lateral tilt towards the glove side = +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z: Rotation toward the glove</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 2.3 Comparison Heatmaps of Pitch Velocity and Torque Correlations

In these plots the top number (top half) in each bold square is the pitch velocity correlation and the bottom number (bottom half) is the torque correlation to the same metric. Each pitch velocity and torque comparison is represented by three heatmaps: the heatmap for postural metric correlations, the heatmap for kinematic metric correlations, and then the condensed heatmap of transverse plane kinematic metric correlations where the shoulder transverse metric is changed from shoulder internal rotation angular velocity to shoulder horizontal adduction angular velocity.

These heatmaps can be used to further categorize metrics into individual, tradeoff, positive, or negative metrics see Part 1: Postural metric and kinematic correlations to velocity and torque for metric definitions. Tradeoff metrics can be categorized as correlations of the same color, which are in the same direction meaning that metric has the same effect on both pitch velocity and torque. Correlations in opposite directions could then be categorized as positive or negative metrics depending on if pitch velocity or torque is being increased. Finally, since an individual metric only affects pitch velocity or torque this occurs when one of the correlations in the pair is at or near zero, while the other correlation has a larger effect on its corresponding metric within the pair. As outlined in Part 1: Summary these metric categorizations can be used to guide pitcher training strategies.
Pitch Velocity and Elbow Varus Torque Correlation Comparison

Correlations of planar kinematics to both pitch velocity (top half) and maximum elbow varus torque before release (bottom half). The largest differences in correlations can be seen for the hand sagittal angular velocity, torso transverse angular velocity, and elbow sagittal angular velocity.

Correlations of planar kinematics to both pitch velocity (top half) and maximum elbow varus torque before release (bottom half). In this graph the shoulder transverse angular velocity has been replaced with the shoulder horizontal adduction velocity. The largest differences in correlations in the transverse plane are the shoulder transverse angular velocity and torso transverse angular velocity.
Correlations of postural metrics to both pitch velocity (top half) and maximum elbow varus torque before release (bottom half). The largest differences in correlations are for shoulder external rotation at release, knee flexion at MER, and shoulder external rotation at MER.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Foot Plant</th>
<th>Max External Rotation</th>
<th>Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion</td>
<td>-0.131</td>
<td>-0.453</td>
<td>-0.385</td>
</tr>
<tr>
<td>Pelvic Forward Tilt</td>
<td>0.067</td>
<td>0.056</td>
<td>0.030</td>
</tr>
<tr>
<td>Trunk Forward Tilt</td>
<td>0.185</td>
<td>0.582</td>
<td>0.559</td>
</tr>
<tr>
<td>Trunk Rotation</td>
<td>0.071</td>
<td>0.159</td>
<td>0.179</td>
</tr>
<tr>
<td>Pelvic Rotation</td>
<td>0.301</td>
<td>0.401</td>
<td>0.252</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td>0.193</td>
<td>0.178</td>
<td>0.286</td>
</tr>
<tr>
<td>Shoulder External Rotation</td>
<td>-0.035</td>
<td>-0.053</td>
<td>-0.108</td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction</td>
<td>0.001</td>
<td>-0.206</td>
<td>-0.091</td>
</tr>
<tr>
<td>Shoulder Abduction</td>
<td>0.080</td>
<td>-0.006</td>
<td>-0.030</td>
</tr>
<tr>
<td>Trunk Lateral Tilt</td>
<td>0.246</td>
<td>-0.136</td>
<td>-0.153</td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction</td>
<td>-0.043</td>
<td>0.035</td>
<td>0.028</td>
</tr>
<tr>
<td>Shoulder External Rotation</td>
<td>-0.338</td>
<td>-0.224</td>
<td>-0.259</td>
</tr>
<tr>
<td>Trunk Lateral Tilt</td>
<td>-0.139</td>
<td>-0.105</td>
<td>-0.130</td>
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<tr>
<td>Shoulder Abduction</td>
<td>-0.032</td>
<td>0.465</td>
<td>0.425</td>
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<tr>
<td>Shoulder External Rotation</td>
<td>-0.107</td>
<td>0.005</td>
<td>0.098</td>
</tr>
<tr>
<td>Trunk Lateral Tilt</td>
<td>-0.070</td>
<td>0.021</td>
<td>0.036</td>
</tr>
<tr>
<td>Shoulder Abduction</td>
<td>-0.106</td>
<td>0.081</td>
<td>0.086</td>
</tr>
<tr>
<td>Shoulder Abduction</td>
<td>-0.020</td>
<td>-0.094</td>
<td>-0.045</td>
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</table>
Pitch Velocity and Shoulder Internal Rotation Torque Correlation Comparison

Correlations of planar kinematics to both pitch velocity (top half) and maximum shoulder internal rotation torque before release (bottom half). The largest differences in correlations can be seen for the hand sagittal angular velocity, elbow sagittal angular velocity, and torso transverse angular velocity.

Correlations of planar kinematics to both pitch velocity (top half) and maximum shoulder internal rotation torque before release (bottom half). In this graph the shoulder transverse angular velocity has been replaced with the shoulder horizontal adduction velocity. The largest differences in correlations in the transverse plane are the shoulder transverse angular velocity and torso transverse angular velocity.
Correlations of postural metrics to both pitch velocity (top half) and maximum shoulder internal rotation torque before release (bottom half). The largest differences in correlations are for knee flexion at MER, shoulder external rotation at release, and shoulder external rotation at MER.
Pitch Velocity and Shoulder Horizontal Abduction Torque Correlation Comparison

Correlations of planar kinematics to both pitch velocity (top half) and maximum shoulder horizontal abduction torque after release (bottom half). The largest differences in correlations can be seen for the elbow sagittal angular velocity, hand frontal angular velocity, and torso transverse angular velocity.

Correlations of planar kinematics to both pitch velocity (top half) and maximum shoulder horizontal abduction torque after release (bottom half). In this graph the shoulder transverse angular velocity has been replaced with the shoulder horizontal adduction velocity. The largest differences in correlations in the transverse plane are the shoulder transverse angular velocity and torso transverse angular velocity.
Correlations of postural metrics to both pitch velocity (top half) and maximum shoulder horizontal abduction torque after release (bottom half). The largest differences in correlations are for pelvic forward tilt at MER, shoulder external rotation at release, and pelvic forward tilt at release.