

THE ACUTE EFFECTS OF A ROTATIONAL MEDICINE BALL THROW
EXERCISE ON BASEBALL PITCHING BIOMECHANICS.

by

AVERY PIERCE ROGERS SULLIVAN

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Exercise Science
with a focus in Biomechanics at
The University of Texas at Arlington

May, 2019

Arlington, Texas

Supervising Committee:

Mark Ricard, Supervising Professor

Priscilla Caçola

Kevin Laudner

ABSTRACT

The acute effects of a rotational medicine ball throw exercise on baseball pitching biomechanics.

Avery Pierce Rogers Sullivan, M.S.

The University of Texas at Arlington, 2019

Supervising Professor: Mark Ricard

The ability to throw at higher velocities with proper mechanics is very advantageous for baseball pitchers to increase performance and decrease injury risk. Pitching utilizes the movement of energy through the kinetic chain, wherein momentum is generated by the proximal core segments of the body and transferred to the distal segments of the throwing shoulder and elbow to produce ball velocity. Medicine ball throws (MBT) have been used as a training method for rotational throwing and striking athletes to improve core strength and power. Rotational MBT are sport-specific for baseball pitching because of the similar explosive sequential muscle activation of the pelvis, torso, and arms. The purpose of this study was to investigate the effects of a side-rotational MBT exercise on pitching biomechanics and ball velocity when performed immediately prior to pitching as a method of post-activation potentiation (PAP). High school, college, and professional aged pitchers ($n = 6$, age 19.5 ± 3.6 years) were randomly assigned to MBT and control (CON) groups. Both groups threw five pre-trial and five post-trial maximal effort fastballs, with the MBT group performing one set of six side-rotational MBT at maximum effort in between the pre and post-trials while the CON group rested. All pitching trials were

recorded by a three-dimensional motion capture system at 240 Hz, from which five temporal, four kinematic, and three kinetic variables were calculated. A 2 x 2 mixed ANOVA for each dependent variable was used for comparisons between and within groups. There were significant interactions between groups and time for peak trunk rotational velocity ($p = .049$), peak elbow extension velocity ($p = .014$), and maximum external rotation torque ($p = .042$). These results may warrant further research into MBT as a method for warming up and eliciting a PAP response for pitching.

TABLE OF CONTENTS

ABSTRACT	ii
TABLE OF CONTENTS	iv
ACKNOWLEDGEMENTS	vi
DEDICATION	vii
CHAPTER 1: INTRODUCTION	1
Performance potential and injury risk associated with baseball pitching	1
The kinetic chain and stretch-shortening cycle in pitching.....	2
Warm-up and training techniques for performance and injury resilience.....	4
CHAPTER 2: LITERATURE REVIEW	7
Effects of the proximal kinetic chain on throwing arm kinetics and ball velocity	7
The effects of different warm-up routines and post-activation potentiation on rotational throwing and striking performance.....	9
The effects of medicine ball throws and plyometrics on rotational power and muscle activation.....	12
Purpose.....	13
CHAPTER 3: METHODS	14
Experimental Approach to the Problem	14
Subjects	15
Procedures.....	16

Data Analysis	21
Statistical Analysis	21
CHAPTER 4: RESULTS	23
CHAPTER 5: DISCUSSION.....	28
APPENDIX	34
REFERENCES.....	36

ACKNOWLEDGEMENTS

I thank Dr. Ricard, my supervising professor, for his guidance and assistance in helping me complete this research study. I also thank Dr. Caçola and Dr. Laudner for their knowledge of research and pushing me in the right direction early on in the research process. Finally, I thank Daniel Evans and Trent Blank for helping me with subject recruitment and data collection at TMI Sports Medicine.

DEDICATION

I dedicate this work to my father Ski Sullivan, mother Libby Rogers, and long-time mentor and friend Donnie Watson. Their unconditional love, support, and endless motivation in academics, baseball, and all facets of life fuels my desire to continually strive to be the best I can be. I certainly would not be where I am today without them.

CHAPTER 1: INTRODUCTION

Performance potential and injury risk associated with baseball pitching

With approximately three million children playing baseball in the United States of America every year, and hundreds of thousands more playing at the high school level and beyond, the need for proper management of throwing-related injuries has grown vastly over the past few decades (Fleisig, Chu, Weber, & Andrews, 2009; Melugin, Leafblad, Camp, & Conte, 2018). Increased injury risk for pitchers has been related to a variety of factors contributing to overuse, including: number of months of pitching per year, pitching frequency, number of competitive innings pitched per year, pitching while fatigued, pitching through arm pain, and other specific details such as playing catcher in addition to pitching and participating in showcase tournaments (Okoroha et al, 2018; Melugin et al, 2018; Fleisig et al, 2010; Olsen, Fleisig, Dun, Loftice, & Andrews, 2006). Additionally, increased injury risk has been associated with a variety of biomechanical traits that can elicit heightened forces and torques at the throwing arm shoulder & elbow during the pitching delivery (Fleisig, Andrews, Dillman, & Escamilla, 1995; Fleisig, Barrentine, Escamilla, & Andrews, 1996).

Performance in baseball pitching is influenced by factors such as ball velocity, ball movement, and control (Fleisig et al, 2016; Werner, Suri, Guido, Meister, & Jones, 2008). It is to the pitcher's advantage to be able to throw at a high velocity while maintaining control and manipulating ball movement. To produce the desired results of higher ball velocity and control consistently, the pitcher has to move their body in a coordinated manner and minimize the variability of their movements from pitch to pitch (Fleisig et al, 2009).

The kinetic chain and stretch-shortening cycle in pitching

The pitching motion consists of a sequence of events wherein the larger lower body and core segments generate rotational forces and transfer energy to the smaller upper body segments (Chu, Jayabalan, Kibler, & Press, 2016). An efficient kinetic chain of the pitching motion is characterized by properly transferring energy from the bigger proximal segments of the body to the smaller distal segments with appropriate timing (MacWilliams, Choi, Perezous, & Chao, 1998). Slight disruptions in timing can greatly affect the transfer of momentum from proximal to distal segments (Fleisig et al, 1996; Aguinaldo, Buttermore, & Chambers, 2007). Therefore, baseball pitchers have to utilize the entire kinetic chain as efficiently as possible in order give themselves the greatest chance for better performance and decreased injury risk as well as consistency and durability (Chu et al, 2016; Fleisig et al, 1996; Seroyer 2010). Other factors that play into the kinetic chain include optimized strength, flexibility, power, motor patterns, muscle activation, and sequential force generation (Sciascia, Thigpen, Namdari, & Baldwin, 2012). If any of these areas are lacking due to muscle weakness or tightness, poor motor control or movement patterns, or fatigue, a higher risk of injury can ensue (Sciascia et al, 2012).

The stretch-shortening cycle (SSC) is a mechanism of human movement commonly used in explosive movement which involves the lengthening or stretching of agonist muscles immediately followed by a rapid concentric contraction (Newton et al, 1997). The SSC has been shown to enhance concentric muscle action via the transfer of elastic energy and the stretch-reflex (Newton et al, 1997). In baseball pitching, the primary occurrence of the SSC is during late arm-cocking just prior to arm acceleration as the musculature around the shoulder stretches into maximal external rotation and then immediately internally rotates (Feltner & Dapena, 1986). Internal rotation of the humerus can reach speeds up to 7700 degrees per second as the result of

the quick, whip-like pre-stretch of the shoulder into external rotation (Fleisig et al, 1996; Seroyer et al, 2010; Matsuo, Escamilla, Fleisig, Barrentine, & Andrews, 2001).

While internal and external rotation of the glenohumeral joint reach the highest angular velocities of any movement during throwing, they are accompanied by other movements that assist in properly positioning the body to exert the force generated from the internal rotation torque as well as the proximal segments of the kinetic chain into the ball at release (Fleisig et al, 1996; Seroyer et al, 2010). Shoulder horizontal abduction occurs during the stride phase and produces a stretch of the anterior side of the throwing shoulder, but then just prior to maximum external rotation a horizontal adduction torque is produced in order to keep the arm moving forward and help transfer momentum from upper torso rotation to the arm (Fleisig et al, 1996; Seroyer et al, 2010; Feltner & Dapena, 1986). The eccentric loading of the anterior shoulder during the horizontal abduction colloquially known as ‘arm lag’ can increase the amount of potential energy that is stored and released in the elastic component of the SSC (Stodden, Fleisig, McLean, & Andrews, 2005, Aguinaldo et al, 2007). The timing of later maximum horizontal adduction during acceleration and earlier maximum shoulder internal rotation around the time of ball release has been correlated with higher ball velocities (Stodden et al, 2005).

While these events are happening during arm cocking, the elbow extensors eccentrically and isometrically contract to resist elbow flexion and then concentrically contract to produce peak elbow extension velocity prior to ball release and peak shoulder internal rotation velocity (Fleisig et al, 1996; Seroyer et al, 2010; Stodden et al, 2005). Additionally, the trunk flexes or tilts further forward in the direction of home plate during arm-cocking and acceleration, which can result in a release point closer towards home plate and allows more time and distance for the

summation of forces and momentum from the kinetic chain to be imparted on the ball (Stodden et al, 2005; Werner et al, 2008; Matsuo et al, 2001). While greater forward trunk tilt, lead leg braking forces, and increased rotational velocities of the pelvis and upper torso can contribute to higher forces and torques at the shoulder and elbow, optimization of the timing of the peak segmental angular velocities in the kinetic chain can serve to attenuate these kinetics (Fortenbaugh, Fleisig, & Andrews, 2009; Post, Laudner, McLoada, Wong, & Meister, 2015). Conversely, poor timing of the proximal kinetic chain or decreased forward trunk tilt and lead leg braking force can prove to be pathomechanical and unnecessarily increase forces and torques at the shoulder and elbow (Chu et al, 2016; Fortenbaugh, Fleisig, & Andrews, 2009). In summary, increased kinematics of the proximal segments rely on proper timing in order to transfer more energy up the kinetic chain to affect ball velocity (Fortenbaugh, Fleisig, & Andrews, 2009).

Warm-up and training techniques for performance and injury resilience

Pitching is a complex, explosive, full-body activity that utilizes linear and rotational movements, and therefore requires proper mobility and strength to minimize injury risk (Chu et al, 2016; Wilk, Meister, & Andrews, 2002). Throwing and pitching produce repeated microtrauma to the muscles, tendons, ligaments, and other joint structures about the hips, trunk, and throwing arm shoulder and elbow (Seroyer et al, 2009). It has been demonstrated that these repetitive stresses from throwing can cause short-term loss in range of motion as well as inflammation (Reinold et al, 2008), and over time can cause structural adaptations (Wilk, Macrina, & Arrigo, 2012). With these demonstrated effects from pitching, the management of mobility and stability in the regions used heavily in pitching becomes even more important for performance and minimizing injury risk (Chu et al, 2016; Wilk et al, 2002; Seroyer et al, 2009).

While methods used for warming up, improving general and sport-specific strength, and maintaining proper flexibility for baseball players are fairly wide-ranging and contentious among different schools of thought, it is generally agreed upon that all of these areas are critical for successful, healthy pitching.

Warming up involves the general preparation of the body for a given exercise or activity (McCrary, Ackermann, & Halaki, 2015). Traditional methods of holding static stretches to increase the range of motion of joints throughout the body have been shown to have negative effects on performance (Wilcox, Larson, Brochu, & Faigenbaum, 2006). Furthermore, there is inconclusive evidence that stretching reduces the risk of injury during exercise or athletic participation (Thacker, Gilchrist, Stroup, & Kimsey, 2004). Therefore, newer warm-up methods generally have a primary focus on raising the core body temperature and increasing how the joints actively move through their range of motion (Thacker et al, 2004; Wilcox et al, 2006). Many modern dynamic warm-up techniques have been tested with the intention of increasing performance variables such as strength, speed, accuracy, power output, and decreased muscle soreness (McCrary et al, 2015). Dynamic movements involving high force and low velocity, isometric, or low force and high velocity can be used as a part of a warm-up prior to physical exertion. These types of movements can elicit the post-activation potentiation (PAP) mechanism of the neuromuscular system which can enhance acute performance (Wilcox et al, 2006; Robbins, 2005). PAP can produce a more excited state of the central nervous system, which can allow for higher strength and power output (Wilcox et al, 2006). However, the rest interval after a PAP warm-up or exercise is performed must be carefully considered, because if it is too short then there is a greater chance that muscle performance will be inhibited due to fatigue (Reyes & Dolny, 2009; Gilmore, Brilla, Suprak, Chalmers, & Dahlquist, 2019). Lastly, the intensity and

volume of the PAP procedure used as well as training status of the individual also factor into the relationship of fatigue and potentiation (Wilcox et al, 2006; Robbins, 2005).

Medicine ball throws (MBT) have gained popularity in recent years as an effective training and rehabilitative tool for rotational throwing and striking athletes (Lehman, Drinkwater, & Behm, 2013; Wilk et al, 2002). More specifically, the side-rotational MBT exercise mimics the sequencing and transfer of energy in the hips, core, and shoulders used in pitching while emphasizing explosive movements that can utilize the SSC (Lehman et al, 2013; Raeder, Fernandez-Fernandez, & Ferrauti, 2015; Wilk et al, 2002). This movement trains rotational power and has been shown to help improve throwing velocity in throwers and pitchers (Escamilla et al, 2012; Raeder et al, 2015).

CHAPTER 2: LITERATURE REVIEW

Effects of the proximal kinetic chain on throwing arm kinetics and ball velocity

Stodden, Fleisig, McLean, Lyman, & Andrews (2001) examined the role of pelvis and upper torso kinematics in producing ball velocity. Their findings showed that a more open position with the pelvis and upper trunk at the time of maximal throwing shoulder external rotation allowed the core segments to contribute more to ball velocity (Stodden et al, 2001). Additionally, they found that faster angular velocities of pelvis and upper trunk rotation as well as a more forward trunk position at ball release were related to higher ball velocity (Stodden et al, 2001). The authors concluded that creating more rotational momentum of the proximal segments allowed for more energy to be transferred through the kinetic chain to the arm during acceleration and ultimately to the ball at release (Stodden et al, 2001). Oyama et al. (2014) displayed that an improper rotation sequence of proximal segments, mainly the pelvis and upper trunk, caused increased proximal force and maximum external rotation angle at the throwing arm shoulder. However, ball speed was not significantly different, indicating that the upper body compensated for an inefficient kinetic chain by increasing forces at the shoulder to produce ball velocity (Oyama et al, 2014). Urbin, Fleisig, Abebe, and Andrews (2012) found significant correlations between upper body forces, ball velocity, and the timing between events such as stride foot contact and peak velocities of various segments in the pitching delivery. Greater time in these specific phases of the pitching motion correlated with decreased forces at the throwing arm shoulder and elbow as well as decreased ball speed (Urbin et al, 2012). These results suggest that increased latency between kinematic variables such as stride foot contact and peak pelvis

rotational velocity can cause decreased performance, but it can also decrease injury risk from excessive torques at the throwing arm shoulder and elbow. These results were expounded upon by Post et al. (2015), who compared ball velocity to forces at the throwing arm shoulder and elbow associated with increased injury risk. Their data indicated that a weak positive correlation existed between one of the three kinetic variables measured and ball velocity, meaning that high velocity can still be achieved without placing excessive forces on the throwing arm shoulder and elbow given that the timing of the pitching motion is efficient (Post et al, 2015).

Matsuo et al (2001) investigated several kinematic and temporal parameters to find what differed between two group of pitchers that had lower versus higher fastball velocities. While none of the linear or angular velocities or timing of the pelvis, upper torso, or elbow were significantly different between the higher and lower velocity groups, it was found that the higher velocity group had a significantly higher lead knee extension velocity and more forward trunk position at the instant of ball release (Matsuo et al, 2001). Similar results were shown by van Trigt, Schallig, Van der Graaf, Hoozemans, and Veeger (2018) for youth pitchers. Their study found that lead knee extension angles were significantly associated with higher ball velocity at the instant of throwing shoulder maximum external rotation and ball release, but not at foot contact (van Trigt et al, 2018). These studies display that when peak lead leg knee extension velocity transpires closely to ball release, it helps provide a stable base for the upper body to rotate on top of (Matsuo et al 2001; van Trigt et al, 2018). This lead leg 'bracing' mechanism is a product of the vertical ground reaction force and the posteriorly directed braking force, both of which can exceed two times the body weight of the pitcher (Guido & Werner, 2012). The force put into the ground by the lead leg in the anterior and vertical directions helps to provide a stable base that facilitates further rotation of the pelvis, upper torso, and distal kinetic chain

(MacWilliams et al, 1998; van Trigt et al, 2018). Logically, the magnitude of the lead leg braking force has also been shown to significantly correlate with higher ball velocity (MacWilliams et al, 1998; Guido & Werner, 2012).

The effects of different warm-up routines and post-activation potentiation on rotational throwing and striking performance

Although pitching is a complex, powerful, full-body rotational motion, the effects of warming up and potentiating the muscles that rotate and stabilize the hips, pelvis, and trunk have not been studied extensively for baseball pitchers. One study by Huang, Pietrosimone, Ingersoll, Weltmen, & Saliba (2011) examined the effects of a sling exercise-based warm-up for the upper body on throwing velocity and accuracy. Their findings did not indicate any significant differences from an active warm-up commonly used by baseball players consisting of light upper-body bands and free weight exercises (Huang et al, 2011). However, the method of the upper-body sling exercise had an added benefit of engaging the core musculature for stabilization (Huang et al, 2011). While the core musculature involved in trunk stabilization does not necessarily play a large role in producing higher pelvis and upper trunk rotational velocities, it is still important for stabilization, transfer of energy, and forward trunk tilt in the pitching delivery (Kibler, Press, & Sciascia, 2006). Further research is needed in this area specific to pitching, but some general insights can be gained from reviewing research studies performed on other types of rotational throwing and striking movements that share similar aspects of utilizing a proximal to distal sequencing of segments in the kinetic chain.

A systematic review of various types of warm-up protocols specifically for the upper body across different sports revealed that dynamic exercises at a higher load had a more positive effect than at a lower load, with maximum isometric contractions also showing a positive effect

on certain performance outcomes (McCrary et al, 2015). Similarly, a study on junior tennis players by Gelen, Dede, Bingul, Bulgan, & Aydin (2012) demonstrated that a high-volume upper body plyometric warm-up significantly increased tennis serve velocity compared to a traditional warm-up. Again, the focus on this study was on the upper extremity, but to absorb the perturbations associated with the ballistic nature of the upper body plyometrics performed, the core stabilization musculature must contract (Kibler et al, 2006). Therefore, it can be hypothesized that the effect of the high-volume upper body plyometric warm-up on activating the muscles involved in stabilizing the trunk provided some portion of the increase in tennis serve velocity (Gelen et al, 2012).

Analysis of swinging various types of weighted bats as a warm-up tool for baseball hitters have shown mixed results on performance, with some studies showing no difference in bat speed and some studies showing improvements (Reyes & Dolny, 2009; Szymanski et al, 2011; Williams et al, 2019). Reyes and Dolny (2009) tested different orders of swinging light, standard, and heavy bats as a warm-up for hitting. Their findings indicated that no specific sequence of swings with different weighted bats was superior, but all different orders increased bat speed over the control group which only swung the standard weight bat (Reyes & Dolny, 2009). Montoya, Brown, Coburn, & Zinder (2009) used a similar range of light, normal, and heavy bat swings as a warm-up tool to test bat speed. However, their study design did not use a pre and post-test method, but rather just compared the three different weights for warm-up swings with a post-test of normal weighted bat swings. Their results showed that swinging the lighter bat resulted in faster bat speed than the normal weight and the normal weight resulted in faster bat speed than the heavy weight (Montoya et al, 2009). The limitation of this study design did not elucidate the time effects of bat speed before and after warm-up swings. Szymanski et

al.(2011) investigated an array of commonly used warm-up tools of varying weights and found that none of the different weights created significantly different bat speed with a normal bat afterwards. Their results differed from other weighted bat studies in that the heavier bats did not show any worse effects on swinging speed than the standard or lighter weights (Szymanski et al, 2011). Southard and Groomer (2003) took a deeper dive into the warming up with differently weighted bats, in that their implements had different moments of inertia. While their results did not show any significant differences for maximum bat speed, bat speed at contact, or bat angle at either time point, they found that the moment of inertia has to be accounted for when choosing a warm-up method for a rotational striking event such as baseball hitting due to the potentially different motor patterns that can emanate from a constraint that is dissimilar from the normal bat to be used in a game (Southard & Groomer, 2003).

Gilmore, Brilla, Suprak, Chalmers, & Dahlquist (2019) took a new approach to potentiating the body for hitting. They used high-intensity isometric contractions in the early phase of the swing with female high school and college softball players. While these isometric contractions did not use as full of a range of motion like the full swings of the previously mentioned hitting studies, the results did indicate that bat speed was significantly higher than baseline values six minutes after the PAP intervention (Gilmore et al, 2019). This study also looked into the relationship between fatigue and potentiation after the usage of a PAP exercise and found that positive effects on bat speed occurred between two and twelve minutes, but peaked at six minutes (Gilmore et al, 2019).

The effects of medicine ball throws and plyometrics on rotational power and muscle activation

Szymanski, Szymanski, Bradrod, Schade, and Pascoe (2007) examined a 12-week full body progressive resistance training program with the addition of MBT in high school baseball players, and the results showed greater improvements in torso rotational and sequential hip, torso, and arm rotational strength for the MBT group than just full-body resistance training alone. The results of Escamilla et al. (2012) displayed that performing only plyometric exercises with medicine balls and elastic bands increased pitching velocity significantly after a six week training program compared to a control group in high school baseball players. Stodden, Campbell, and Moyer (2008) measured the rotational velocities of the pelvis and upper torso as well as the angle of separation between the two segments, commonly referred to during pitching as ‘hip-shoulder separation.’ When compared with other common rotational core exercises, the side rotational MBT exercise produced the highest pelvis and upper trunk rotational velocities and thus displayed a very good sport-specific applicability to throwing and pitching (Stodden et al, 2008).

Multiple studies have displayed the importance of gluteal musculature activation in stabilizing the pelvis, as well as correlating with activation of the muscles that support the scapulae during pitching (Oliver, Weimar, & Plummer, 2015; Plummer & Oliver, 2014). Proper gluteal muscle function during the pitching motion is crucial, as lack thereof can have negative implications for performance and injury risk to the upper and lower extremities (Oliver et al, 2015). Ghigiarelli, Rothstein, Ng, Burke, & Sell (2014) examined levels of activity of the gluteus maximus and gluteus medius muscles using electromyography while using three different common rotational power training implements for golfers. Of the three implements, side-

rotational MBT, produced the highest gluteus maximus and gluteus medius muscle activation expressed as a percentage of the maximum isometric voluntary contraction for the methods examined (Ghigiarelli et al, 2014). This data indicates that performing rotational MBT at a high velocity will stimulate the gluteal muscle fibers to a great degree.

Purpose

While there is a growing level of evidence indicating that dynamic exercises can help improve performance outcome measures, no known studies have investigated MBT as a method of potentiating the kinetic chain for baseball pitchers immediately prior to pitching on a mound. The purpose of this study was to investigate the effects of performing a rotational MBT exercise versus a control group that did not perform the MBT on performance outcome and production variables of the pitching motion in high school, collegiate, and professional baseball pitchers. This research study design differs from the current literature in that the MBT will not be used as a core strength and power training mechanism, but rather as a way to activate and potentiate the pelvic and core musculature with a high velocity rotational movement that mimics the proximal to distal sequencing of the kinetic chain in baseball pitching. The biomechanical variables chosen for this study have been shown to have implications for performance and injury risk in pitchers (Escamilla, Fleisig, Groeschner, & Akizuki, 2017; Fleisig et al, 1995; Fleisig et al, 1996; Urbin et al, 2012), while ball velocity is widely accepted as an important performance outcome variable for pitchers (Escamilla et al, 2017). I hypothesized that the side rotational MBT would increase the efficiency of the throwing motion by increasing ball velocity, decreasing time between peak pelvic rotational velocity and peak upper trunk rotational velocity, and decreasing shoulder and elbow kinetics.

CHAPTER 3: METHODS

Experimental approach to the problem

This research study examined the effects of performing a side-rotational medicine ball throw exercise versus a control group that did not perform the MBT protocol, with respect to time, on one performance outcome and thirteen biomechanical dependent variables. The biomechanical variables were made up of five temporal variables, four kinematic variables, and four kinetic variables. Temporal variables for peak segment angular velocity were expressed as a percent of the Pitching Cycle (%PC), from Foot Contact (0%) to Ball Release (100%). There were some temporal values that occurred before foot contact which were expressed as negative percent values as well as some that happened after ball release which were expressed as values greater than 100 percent. The temporal variable for time difference between peak segment angular velocities was expressed in milliseconds (ms). Kinematic variables for peak segment angular velocity were expressed in degrees per second (deg/s). Kinetic variables for force and torque were normalized to body weight (bw) and body weight multiplied by height (bw-h), respectively, for each individual subject. The performance outcome variable for ball velocity was expressed in miles per hour (mph).

<u>Biomechanical Variables</u>			<u>Performance Outcome Variable</u>
<u>Temporal</u>	<u>Kinematic</u>	<u>Kinetic</u>	
Peak Pelvis Rotational Velocity Timing (%PC)	Peak Pelvis Rotational Velocity (deg/s)	Max Shoulder Distraction Force (bw)	Ball Velocity (mph)
Peak Trunk Rotational Velocity Timing (%PC)	Peak Trunk Rotational Velocity	Max Shoulder External Rotation Torque (bw-h)	
Peak Elbow Extension Velocity Timing (%PC)	Peak Elbow Extension Velocity (deg/s)	Max Elbow Flexion Torque (bw-h)	
Peak Pelvis Rotational Velocity Timing (%PC)	Peak Shoulder Internal Rotation Velocity (deg/s)	Max Elbow Valgus Torque (bw-h)	
Peak Pelvis to Peak Trunk Rotational Velocity Difference (ms)			

Table 1. Outline of dependent variables.

Subjects

This experiment was conducted with the approval of the Institutional Review Board of the University of Texas at Arlington (IRB Protocol #2019-0076, IRB Approval Date 11/27/2018). High school, collegiate, and professional pitchers were recruited via flyers posted at TMI Sports Medicine. All participants had a minimum of three years of competitive pitching experience, were healthy at the time of participation, meaning they were cleared by physician or physical therapist to return to sport participation for any injuries that had occurred within the past twelve months, and were throwing regularly, which was defined as at least two times per week

for four weeks immediately prior to participation. Written informed consent was acquired prior to participation. At the beginning of the session, an information form and questionnaire was completed by all participants. This included questions regarding inclusion criteria as well as height, weight, familiarity with medicine ball throw exercises, and if they were primarily a starting or relief pitcher.

	All Subjects (n=6)		CON (n=3)		MBT (n=3)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	19.5	3.6	17.0	1.0	22.0	3.5
Height (cm)	188.8	7.3	190.5	7.6	187.1	8.2
Weight (kg)	89.1	13.8	80.1	14.6	98.0	5.2

Table 2. Mean and standard deviation values for age, height, and weight for all subjects, control group, and MBT group.

Procedures

The participants were instructed to take as much time as they desired to perform a warm-up to prepare to pitch exactly how they would warm-up before a game. They were provided with access to all of the equipment and space at TMI Sports Medicine, including various types of elastic bands for upper extremity and shoulder exercises, foam rollers and other devices used for self-myofascial release, and indoor and outdoor turf areas where they could perform full-body dynamic and static stretches and throw at a maximum distance of 200 feet as desired. Upon the completion of their warm-up, the participants removed their shirt and shorts, as only compression shorts, socks, shoes, the hat provided, and a baseball glove were worn during the

motion capture. Next, the 38-marker full-body reflective marker set was applied to specific landmarks on the body.

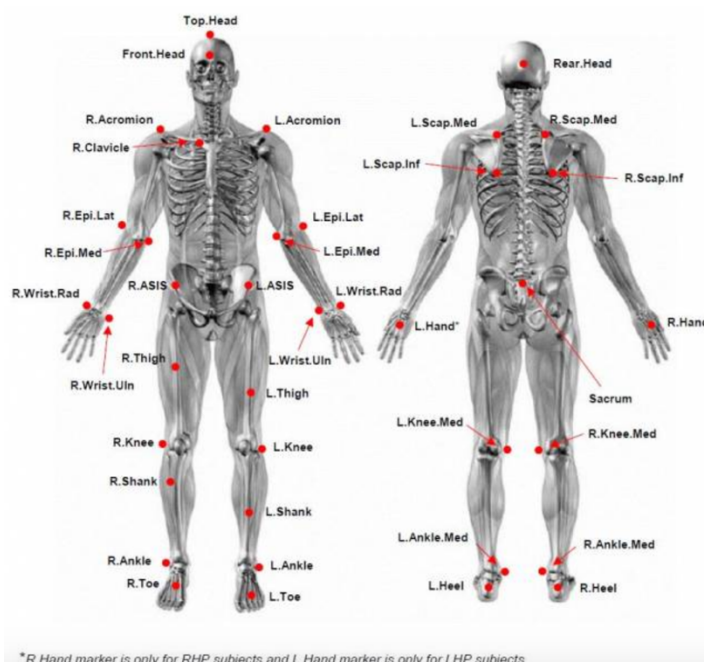


Figure 1. Full body PitchTrak marker set for right-handed pitchers. Markers were placed as follows: hat (3), shoulders (2), clavicle (1), elbows (4), wrists (4), throwing hand (1), scapulae (4), pelvis (3), thighs (2), knees (4), lower leg (2), ankles (4), heels (2), foot (2).

The pitching trials were recorded with an 8-camera (Eagle cameras - Motion Analysis Co., Santa Rosa, CA) 3-dimensional motion capture system at TMI Sports Medicine (Arlington, Tx) at 240 Hz. The cameras were positioned and aimed to allow a central 3 x 2 x 2.5 meter (length x width x height) capture volume. Seed and wand calibration of the capture volume was performed. Digitization of the markers via direct linear transformation (Feltner & Dapena, 1986) was performed by the software package Cortex (Motion Analysis Co., Santa Rosa, CA). The PitchTrak marker set was identified, cleaned, gap-filled, and smoothed using a low-pass Butterworth filter with a cut-off frequency of 12 Hz, similar to previous research studies with similar capture frequencies (Fleisig et al, 2009; Kung et al, 2017).

After the preparation for motion capture was complete, static and functional trials were performed to help make the marker set more robust for automatic tracking of the markers. The static trial consisted of the participant standing in a 'T-pose' with feet shoulder width apart and both arms straight out to the side at shoulder height with the palms pointed forward. The functional trial consisted of the participants standing in the T-pose and performing two lunges, two hip circles in each direction, two jumping jacks, and two shoulder internal and external rotations at 90 degrees of shoulder abduction. Then, the participants threw warm-up pitches on the mound until they signaled that they were ready to throw at maximal effort. All pitches were performed on a portable turf mound (ProMounds Inc, Brockton, MA) built to the specifications of a Major League Baseball mound: ten inches tall at the rubber, with a downward slope of one inch per foot beginning six inches in front of the pitching rubber in the direction facing home plate (Pitcher's mound, 2007). Ball velocity was recorded for all pitches using a Stalker Sport radar gun (Applied Concepts Inc., Richardson, TX). All pitches were thrown from the mound into a target net behind home plate, which was positioned 54 feet from the pitching rubber instead of the standard 60 feet 6 inches due to limitations in laboratory space.

All recorded pitches were performed from the stretch position (opposite of the wind-up), with the participant starting in the T-pose position before coming set and throwing the pitch. This was done to enhance the quality of the automated marker tracking in Cortex. The pre-trial pitches consisted of five maximal effort fastballs that were deemed quality pitches by the investigators. A quality pitch was defined as a pitch that would be able to be caught by the catcher and did not bounce in front of home plate.

Immediately after completion of the five pre-trial pitches, the MBT group was familiarized with the side-rotational medicine ball throw exercise. The side-rotational medicine

ball throws were performed with a four pound medicine ball thrown in the direction opposite of the dominant throwing arm for each subject, as to mimic the direction of rotation during the pitching motion (left for right-handed pitchers, right for left-handed pitchers).

The participants were instructed to look at the wall around their chest height for the duration of the MBT. Each throw started with the participant facing perpendicular to the wall with the medicine ball held out in front at the body's midline with the elbows stiff but flexed slightly. To initiate the throw, the participants counter-rotated to bring the medicine ball back and away from the wall while still looking over their front shoulder at the target, and then rapidly accelerated and released the medicine ball toward the wall. The knees were allowed to bend during the throw but the eyes stayed fixated on the wall and the feet were not supposed to move until after the ball was released.



Figure 2. Technique for the side-rotational MBT exercise. Beginning position (top left), counter-rotation (top right), acceleration (bottom left), and release (bottom right).

After receiving instructions, the MBT group performed a warm-up set of two throws at 50% effort and two throws at 75% effort. The MBT group rested for one minute between the warm-up set and the maximal effort set. The maximal effort set of side-rotational medicine ball throws involved six throws with less than 10 seconds of rest between each throw. After completion of the maximal effort side-rotational medicine ball throw exercise, the MBT group

rested for five minutes. The control group did not perform the medicine ball throw exercise and were given five minutes of rest following the pre-trial pitches.

Following the rest period, both groups performed up to five additional warm-up pitches before the post-trial of five maximal effort fastballs were recorded. The post-trial pitches were performed in exactly the same manner as the pre-trial pitches. Upon completion of the post-trial pitches, the marker set was removed and the session was concluded.

Data Analysis

All temporal and kinematic dependent variables were calculated using code written in Matlab (MathWorks, Natick, MA), which processed tab delimited files of the motion capture data that were output from Cortex. The remaining kinetic dependent variables were calculated using the PitchTrak application (Motion Analysis Co., Santa Rosa, CA), which outputs reports from the motion capture data from Cortex. The temporal variables were a product of the definitions of the pitching cycle, which started at the foot contact (FC) event and ended at the ball release (BR) event. Foot contact was defined similarly to previous research, with the event occurring at the first frame after the lead heel velocity in the anterior-posterior direction crossed zero, which indicated that the foot was firmly planted on the ground (Fleisig et al, 2009). Ball release was defined similarly to previous research as the second frame after the marker on the throwing hand had passed the throwing wrist joint center in the anterior direction (Fleisig et al, 2009).

Statistical Analysis

For all dependent variables, the average values were calculated from the five pre-trials and five post-trials for both groups with the exception of one subject that had a trial that was deemed unusable. This subject's remaining four trials were averaged for analysis. Data for trials

was deemed unusable and thrown out of the analysis if excessive ghosting and occlusion of the marker tracks made cleaning and gap filling of the markers such that the data was visibly skewed. The average values for pre-trial and post-trial for each subject were used for comparisons between and within groups.

The data was checked for normal distribution using Microsoft SPSS (IBM Corporation, Armonk, NY). One trial was removed for having Z-scores of 6.19 for the maximum elbow flexion torque and 7.15 for the maximum elbow valgus torque. The remaining four trials for this subject were averaged for analysis.

The data was analyzed with a 2 x 2 mixed ANOVA for each dependent variable, with 2 between subjects variables for group (MBT and control) and 2 within subjects variables for time (pre-trial and post-trial). An alpha value of $p < .05$ was set for significance. All means, standard deviations, and ANOVAs were performed in R Studio (RStudio, Inc., Boston, MA).

CHAPTER 4: RESULTS

There were significant differences between groups for peak trunk rotational velocity timing ($p = .047$), peak elbow extension velocity timing ($p = .016$), ball velocity ($p = .037$), and maximum external rotation torque ($p = .022$). There were significant interactions between groups and time for peak trunk rotational velocity ($p = .049$), peak elbow extension velocity ($p = .014$), and maximum external rotation torque ($p = .042$).

	CON				MBT			
	Pre		Post		Pre		Post	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ball Velocity (mph)	76.3	1.8	75.1	0.8	80.9	3	81.1	2.6
Pelvis Timing (%PC)	5.1	27	8.5	24.8	22.5	9.8	22.4	10.1
Trunk Timing (%PC)	26.1	4.6	25.6	9.4	40.8	6.9	41.5	6.3
Elbow Extension Timing (%PC)	95.2	0.9	95.4	1.4	92.6	0.7	92.6	0.1
Shoulder Rotation Timing (%PC)	101	5	101.8	5.7	98.9	1	98.9	1
Pelvis Trunk Diff (ms)	25.8	33.5	22.5	37.5	28.3	12.4	29.2	11.5
Peak Pelvis Rotation Velocity (deg/s)	742.1	234.6	734	245.2	659.8	98.5	657.1	98.1
Peak Trunk Rotation Velocity (deg/s)*	1099.8	94	1081.4	76.6	1027.4	79.8	1037.3	79.1
Peak Elbow Extension Velocity (deg/s)*	2836.9	268.7	2779.4	248.1	2900.5	74.6	2945	82.6
Peak Shoulder IR Velocity (deg/s)	4928.3	1955.8	4826.3	948	5013	102.6	5022.2	115.3
Max Shoulder Distraction Force (bw)	144.8	30.3	136.9	25.7	148.8	2.5	152	8.1
Max Shoulder ER Torque (bw-h)*	7.1	0.3	6.9	0.3	7.8	0.4	8	0.2
Max Elbow Flexion Torque (bw-h)	7.9	0.9	7.3	0.3	8	0.2	8.3	0.3
Max Elbow Valgus Torque (bw-h)	5.5	0.5	5.6	0.4	6.2	0.1	6.4	0.3

Table 3. Dependent variable mean and standard deviation values for CON and MBT groups for Pre and Post-Trials. * indicates significant interactions between groups and time ($p < 0.05$).

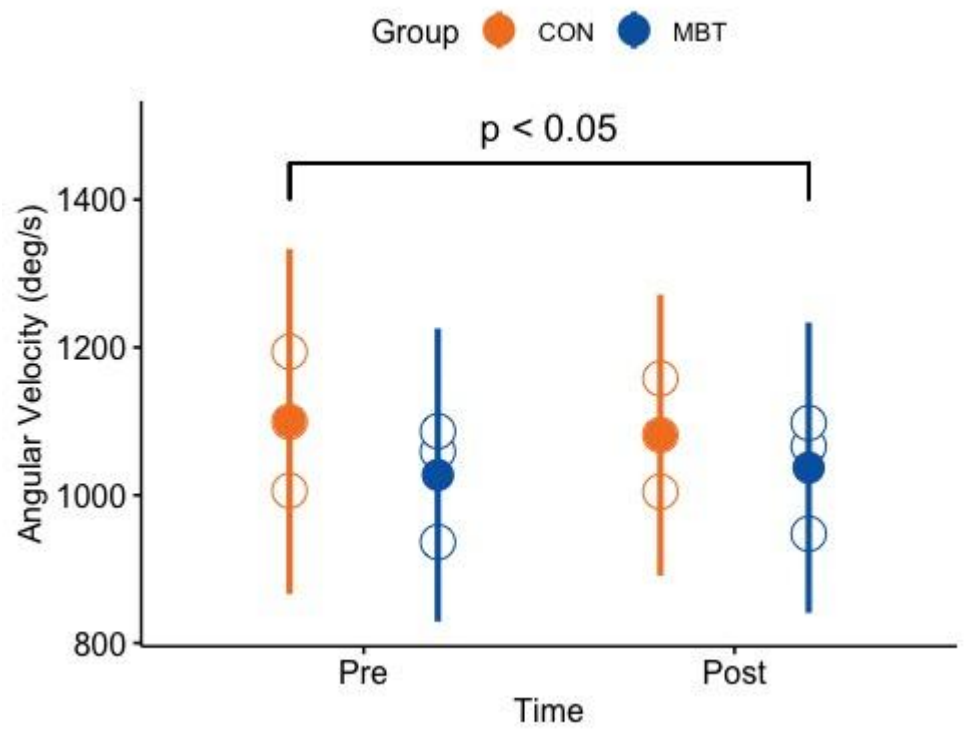


Figure 3. Peak trunk rotation velocity in degrees per second. CON decreased from Pre (1099.8 ± 94 deg/s) to Post (1081.4 ± 76.6 deg/s) and MBT increased from Pre (1027.4 ± 79.8 deg/s) to Post (1037.3 ± 79.1 deg/s). There was a significant interaction between group and time ($p = .049$).

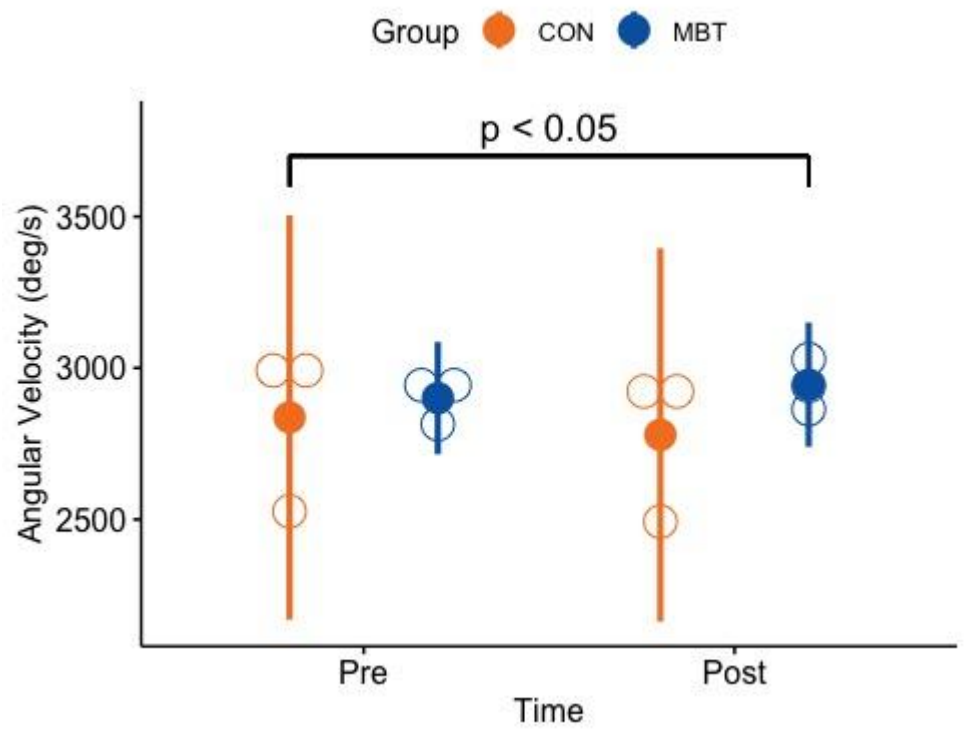


Figure 4. Peak elbow extension velocity in degrees per second. CON decreased from Pre (2836.9 ± 268.7 deg/s) to Post (2779.4 ± 248.1 deg/s) and MBT increased from Pre (2900.5 ± 74.6 deg/s) to Post (2945 ± 82.6 deg/s). There was a significant interaction between group and time ($p = 0.014$).

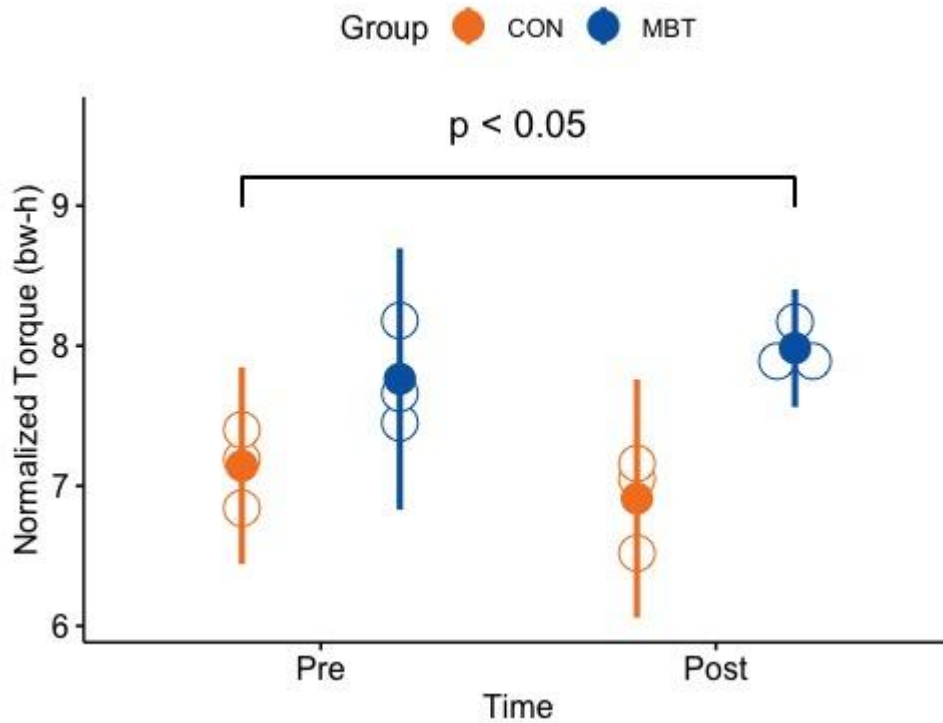


Figure 5. Normalized maximum shoulder external rotation torque expressed as body weight multiplied by height. CON decreased from Pre (7.1 ± 0.3 bw-h) to Post (6.9 ± 0.3 bw-h) and MBT increased from Pre (8.0 ± 0.2 bw-h) to Post (8.3 ± 0.3 bw-h). There was a significant interaction between group and time ($p = .042$).

CHAPTER 5: DISCUSSION

The purpose of this study was to explore the effects of a rotational MBT exercise on pitching biomechanics and ball velocity when performed immediately prior to pitching. The resulting acute changes were compared within subjects before and after the MBT were performed as well as between groups with a control group that did not perform the MBT exercise. Although this study was heavily limited by a very small sample size, the significant increases in peak trunk rotation velocity and peak elbow extension velocity, and maximum shoulder external rotation torque seen in the MBT group may warrant further research. Any speculation as to how much of these kinematic and kinetic differences might have been a direct or indirect result of the MBT intervention is purely theoretical at this point.

Additionally, levels of fatigue were not measured for either group at any point during the study. With fatigue being a limiting factor for PAP and pitching performance in general, future studies with similar methods for investigating the acute effects of PAP or exercises such as MBT on pitching should include ratings of perceived exertion or other practical methods for measuring fatigue.

Although the primary intention of the MBT protocol in this study was to stimulate the muscles and tissues responsible for producing pelvis and trunk rotation in the pitching motion and elicit a PAP response, some fatigue of those muscles from performing maximum effort rotational MBT likely resulted as well. The rest period following the MBT intervention was designed in accordance with previous research for similar types of PAP that reported optimal results for enhanced power output, presumably due to a maximized PAP effect and a minimized

fatigue effect (Gilmore et al, 2019). It is possible that some subjects experienced more fatigue than others in this study, but with a five minute rest interval between the MBT protocol and the pitching post-trials it is unlikely that the MBT protocol caused more than a low amount of fatigue. Subjects could also have accumulated fatigue from throwing or resistance training in the days leading up to participation in this study. The subjects in this study were asked to refrain from excessive throwing or training for two days leading up to this study, but it was not listed as exclusion criteria. If any of the participants did have residual soreness or altered range of motion or movement patterns from throwing, pitching, or resistance training in the days leading up to their participation in this study, that could have contributed to a quicker onset of fatigue from pitching and potentially less effective PAP from the MBT protocol. Monitoring fatigue and activity levels in the two to seven days leading up to participation could also help control for these potential detrimental effects in future studies.

Erickson et al (Erickson 2016) documented the effects of fatigue in a simulated game on adolescent pitchers. Their results indicated that as fatigue increased, proximal segments of the kinetic chain fatigued and ball velocity decreased but arm kinematics did not change. Limitations of their study included using two-dimensional video analysis for kinematics, so with three-dimensional capabilities it is possible that the authors might have found a change in certain shoulder and elbow kinetics with the decrease in ball velocity and less efficient proximal segment kinematics. Other previous studies have shown conflicting results for kinematic and kinetic changes with fatigue in college pitchers (Escamilla et al, 2007; Grantham, Byram, Meadows, & Ahmad, 2014). However, these studies do concur that more mature pitchers generally have a better ability to overcome biomechanical changes that may or may not occur as fatigue sets in to continue producing ball velocity, possibly through changes in stride length or

compensatory mechanisms in the kinetic chain (Crotin, Kozlowski, Horvath, & Ramsey, 2014; Oyama et al, 2014). Variability in pitching kinematics generally decreases with age and maturity (Fleisig et al, 2009). While this is more desirable in theory for decreasing injury risk and improving performance, there is not significant evidence of a concurrent reduction of variability in kinetics in more mature pitchers (Fleisig et al, 2009).

The pitchers used in this study were randomly assigned to the experimental or control group in an alternating fashion, meaning that if one subject was randomly assigned to the MBT group then the next subject would be assigned to the CON group then the following subject would be randomly assigned. However, a huge limitation was that data collected for four subjects was determined to be unusable due to very high residuals of the motion capture data causing excessive ghosting and occlusion of markers. This contributed to the difference in mean age for the groups (CON: 17 ± 1.0 years, MBT: 22 ± 3.5 years). The subjects in this study included high school, college, and professional pitchers between the ages of 16 and 25, which includes a reasonably wide range of maturity and skill level. Future investigations for the acute effects of MBT for pitching biomechanics should also examine differences between less mature youth and high school pitchers and more mature college and professional pitchers.

There was a significant interaction between groups and time for maximum shoulder external rotation torque, with the MBT group increasing and the CON group decreasing from the pre-trials to the post-trials. Ball velocity was significantly different between groups, but did not show a significant interaction of groups and time even though CON slightly decreased (Pre: 76.3 ± 1.8 mph, Post: $75.1 \pm .8$ mph) and MBT slightly increased (Pre: 80.9 ± 3.0 mph, Post: 81.1 ± 2.6 mph). Although some studies have shown increased kinetics with increased ball velocity, others have found little to no positive correlation between the two and rather suggested that

increased forces and torques at the shoulder and elbow of the throwing arm are more likely to result from improper mechanics than increased ball velocity (Fleisig et al, 1995; Oyama et al, 2014; Post et al, 2015). The interrelationship between ball velocity, sequencing of the kinetic chain, and throwing arm kinetics is quite complex and requires a more granular breakdown.

Stodden et al (2005) found that shoulder proximal force and elbow flexion torque significantly increased with ball velocity and served primarily to resist distraction of the shoulder and elbow and control the rate of elbow extension toward the end-range of motion. More optimal positioning of the legs, pelvis, and trunk provide a platform on which more momentum can be transferred to the arm and into the ball at release, which would imply that the rotator cuff, biceps brachii, and other musculature of the shoulder and elbow would need to contract to a greater degree to resist shoulder and elbow distraction and control elbow extension (Stodden et al, 2001). However, more optimal positioning and timing of the scapula, shoulder and elbow may help prevent increased transfer of energy from the proximal segments in the kinetic chain from causing increased shoulder external rotation torque and elbow valgus torque (Post et al, 2015).

Several studies have looked at intra-individual differences in the pitching motion. Changing the effort level, ball velocity, stride length, and a variety of other factors have proven to be associated with changes in kinematics, kinetics, and temporal parameters (Oyama et al, 2014; Fleisig et al, 2009; Fleisig et al, 2016). Clearly, efficient timing of the kinetic chain is critical for producing higher levels of force and velocity without excessively increasing joint loads (Sciascia et al, 2012). While some studies have outlined ranges of appropriate peak segment velocities and kinematics such as hip-shoulder separation for maximal ball velocity, many differences can occur throughout the pitching motion between subjects and from one pitch to the next within subjects. Future studies should investigate optimal timing of the temporal

variables for individual pitchers across different levels of maturity and look for correlations in anthropometrics, mobility, strength, power, and training status.

Another limitation of this study was that event definitions for foot contact and ball release were based solely on the three-dimensional motion capture data. When available, other research studies have defined foot contact with the use of force plates, which is much more logical and accurate than using the velocity of the front foot markers (Guido & Werner, 2012; MacWilliams et al, 1998). Ball release was identified without the use of reference video or reflective markers on the baseball being pitched, which adds another degree of guesswork to the definition of the pitching cycle. To reliably identify the percentage of the pitching cycle at which different peak angular velocities occur, the foot contact and ball release events must be defined more accurately than in this study. Lastly, a faster capture rate than 240 Hz for the motion capture cameras might be desirable for increased measurement accuracy for timing in the pitching motion.

The side-rotational MBT exercise used in this study was chosen for its specificity for baseball. Using a relatively light weight of four pounds allowed the subjects to explosively mimic the sequential movements of the proximal segments of the kinetic chain (Stodden et al, 2008). Measuring muscle activation levels was outside the scope of this study, but past studies have displayed high levels of electromyography (EMG) for the gluteal muscle group during a similar MBT performed explosively (Ghigiarelli et al, 2014). The gluteal muscle group along with the muscles of the core are very important for stability of the lumbopelvic region, which has been correlated with injuries in professional baseball pitchers (Chaudhari, McKenzie, Pan, & Oñate, 2014). Future research should investigate the degree of muscle activation in the gluteus maximus and medius for different types of MBT as well as the potential effects of MBT training on lumbopelvic control and stability.

The method of PAP used in this study was using an explosive force of high velocity for the core with a light MBT exercise. The intensity was supplied by the velocity of the movement with a light weight medicine ball and the load was kept lower in an attempt to avoid a fatigue response. Previous studies on PAP for the lower and upper body have utilized various plyometrics and explosive movements as well as isometric contractions to elicit acute enhanced muscular performance (Wilcox et al, 2006). Different types of MBT variations should be tested as methods for PAP in future studies to test their effectiveness and applicability for pitching performance. Other types of lower body and upper body plyometrics and core isometrics should also be investigated as methods of PAP for pitching.

APPENDIX

MatLab function 'ReadDat' for calculating kinematic and temporal variables from tab delimited files exported from Cortex.

```

“function [ M ] = ReadDat( Subject , Con )
%ReadDat Reads data file

path = '/Users/averysullivan/Desktop/MBT files/';
%path = '/Users/averysullivan/Downloads/';
Eventsfile = [ path 'S' int2str(Subject) Con 'Events.csv' ];
E = csvread(Eventsfile);
%(S1PreEvents.csv) Eventsfile is .csv file for each Subject and Condition
% 1FC 2BR.

for Trial = 1:5
    %Trial = first:last -> first through last trial # for Subject/Condition
    filename = [ path 'S' int2str(Subject) '.Trimmed_' Con 'Trial' int2str(Trial) '.data'];
    M = dlmread(filename, '\t', 5, 0);
    %Opens filename
    %M is array with entire Data file in it
    FC=E(Trial,1);
    BR=E(Trial,2);
    %FC is in column 1, BR is in column 2

    PelvisRotVelo=M(:,60);
    TrunkRotVelo=M(:,61);
    ShoulderRotVelo=M(:,62);
    ElbowExtVelo=M(:,34);
    %Reads in all rows (:) for columns for pelvis, trunk, shoulder rotation, and elbow ext
    velocity from
    %data file

    [minpelvis,locminpelvisrot]=min(PelvisRotVelo)
    [mintrunk,locmintrunkrot]=min(TrunkRotVelo)
    [minelbowext,locminelbowext]=min(ElbowExtVelo)
    [maxshoulderrot,locmaxshoulderrot]=max(ShoulderRotVelo)
    %Finds value and location of peak pelvis rot, trunk rot, elbow ext,
    %and shoulder rotation velocities

    peakpelvis = abs(minpelvis)

```

```

peaktrunk = abs(mintrunk)
peakelbowext = abs(minelbowext)
peakshoulderIR = abs(maxshoulderrot)
%Calculates absolute value for peak pelvis, trunk, elbow ext, and
%shoulder IR velo

trunkpelvisdiff = 1000*(locmintrunkrot - locminpelvisrot)*1/240;
%shouldertrunkdiff = 1000*(locmaxshoulderrot - locmintrunkrot)*1/240;
%Calcs diff between pelvis, trunk, and shoulder rotation velocity in ms

PitchCycle = (BR - FC);
PelvisTiming = (locminpelvisrot - FC) / PitchCycle * 100 ;
TrunkTiming = (locmintrunkrot - FC) / PitchCycle * 100 ;
ShoulderTiming = (locmaxshoulderrot - FC) / PitchCycle * 100 ;
ElbowTiming = (locminelbowext - FC) / PitchCycle * 100 ;
%Pitch Cycle is Ball release minus foot contact (frames)
%Timing is frame # of peak angular velocity - FC / pitch cycle * 100
%expressed as a percentage of the pitch cycle

fileID = fopen('MBTstats.csv','a');
%Opens stats.csv file & 'a' appends data to the end of the existing file
fprintf(fileID,'%d %s %d %f %f %f %f %f %f %f %f\n', Subject , Con , Trial ,
PelvisTiming , TrunkTiming , ElbowTiming, ShoulderTiming, trunkpelvisdiff,
peakpelvis, peaktrunk, peakelbowext, peakshoulderIR);
% %d is integer, %s is string, %f is float (8 decimal places)
%Each dependent variable needs its own %f

fclose(fileID);

end

end”

```

REFERENCES

- Aguinaldo, A. L., Buttermore, J., & Chambers, H. (2007). Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *Journal of Applied Biomechanics*, 23(1), 42-51. doi:10.1123/jab.23.1.42
- Chaudhari, A. M., McKenzie, C. S., Pan, X., & Oñate, J. A. (2014). Lumbopelvic control and days missed because of injury in professional baseball pitchers. *The American Journal of Sports Medicine*, 42(11), 2734-2740. doi:10.1177/0363546514545861
- Chu, S. K., Jayabalan, P., Kibler, W. B., & Press, J. (2016). The kinetic chain revisited: new concepts on throwing mechanics and injury. *PM&R*, 8(3S), S69-S77. doi:10.1016/j.pmrj.2015.11.015
- Crotin, R.L., Kozlowski, K., Horvath, P., & Ramsey, D.K. (2014). Altered stride length in response to increasing exertion among baseball pitchers. *Medicine & Science in Sports & Exercise*, 46(3): 565-71, doi:10.1249/MSS.0b013e3182a79cd9
- Escamilla, R. F., Barrentine, S. W., Fleisig, G. S., Zheng, N., Takada, Y., Kingsley, D., & Andrews, J. R. (2007). Pitching biomechanics as a pitcher approaches muscular fatigue during a simulated baseball game. *The American Journal of Sports Medicine*, 35(1), 23-33. doi:10.1177/0363546506293025
- Escamilla, R. F., Fleisig, G. S., Groeschner, D., & Akizuki, K. (2017). Biomechanical comparisons among fastball, slider, curveball, and changeup pitch types and between balls and strikes in professional baseball pitchers. *The American Journal of Sports Medicine*, 45(14), 3358-3367. doi:10.1177/0363546517730052
- Escamilla, R. F., Ionno, M., DeMahy, M. S., Fleisig, G. S., Wilk, K. E., Yamashiro, K., ... Andrews, J. R. (2012). Comparison of three baseball-specific 6-week training programs on throwing velocity in high school baseball players. *Journal of Strength and Conditioning Research*, 26(7), 1767-1781. doi:10.1519/jsc.0b013e3182578301
- Feltner, M. & Dapena, J. (1986). Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *International Journal of Sport Biomechanics*, 2(4), 235-259. doi:10.1123/ijsb.2.4.235
- Fleisig, G. S., Andrews, J. R., Dillman, C. J., & Escamilla, R. F. (1995). Kinetics of Baseball Pitching with Implications About Injury Mechanisms. *The American Journal of Sports Medicine*, 23(2), 233-239. doi:10.1177/036354659502300218

- Fleisig, G. S., Barrentine, S. W., Escamilla, R. F., & Andrews, J. R. (1996). Biomechanics of Overhand Throwing with Implications for Injuries. *Sports Medicine*, 21(6), 421-437. doi:10.2165/00007256-199621060-00004
- Fleisig, G., Chu, Y., Weber, A., & Andrews, J. (2009). Variability in baseball pitching biomechanics among various levels of competition. *Sports Biomechanics*, 8(1), 10-21. doi:10.1080/14763140802629958
- Fleisig, G. S., Andrews, J. R., Cutter, G. R., Weber, A., Loftice, J., McMichael, C., ... Lyman, S. (2010). Risk of serious injury for young baseball pitchers: a 10-year prospective study. *The American Journal of Sports Medicine*, 39(2), 253-257. doi:10.1177/0363546510384224
- Fleisig, G. S., Laughlin, W. A., Aune, K. T., Cain, E. L., Dugas, J. R., & Andrews, J. R. (2016). Differences among fastball, curveball, and change-up pitching biomechanics across various levels of baseball. *Sports Biomechanics*, 15(2), 128-138. doi:10.1080/14763141.2016.1159319
- Fortenbaugh, D., Fleisig, G. S., & Andrews, J. R. (2009). Baseball pitching biomechanics in relation to injury risk and performance. *Sports Health: A Multidisciplinary Approach*, 1(4), 314-320. doi:10.1177/1941738109338546
- Gelen, E., Dede, M., Bingul, B.M., Bulgan, C., & Aydin, M. (2012). Acute effects of static stretching, dynamic exercises, and high volume upper extremity plyometric activity on tennis serve performance. *Journal of Sports Science and Medicine*, 11(4), 600-605.
- Ghigiarelli, J., Rothstein, A., Ng, J., Burke, J., & Sell, K. (2014). Electromyography activity of gluteus maximus and gluteus medius muscles using the somax power hip trainer in collegiate golfers. *International Journal of Golf Science*, 3(1), 50-63. doi:10.1123/ijgs.2013-0003
- Gilmore, S. L., Brilla, L. R., Suprak, D. N., Chalmers, G. R., & Dahlquist, D. T. (2019). Effect of a high-intensity isometric potentiating warm-up on bat velocity. *Journal of Strength and Conditioning Research*, 33(1), 152-158. doi:10.1519/jsc.0000000000002855
- Grantham, W. J., Byram, I. R., Meadows, M. C., & Ahmad, C. S. (2014). The impact of fatigue on the kinematics of collegiate baseball pitchers. *Orthopaedic Journal of Sports Medicine*, 2(6), 232596711453703. doi:10.1177/2325967114537032
- Guido, J. A., & Werner, S. L. (2012). Lower-extremity ground reaction forces in collegiate baseball pitchers. *Journal of Strength and Conditioning Research*, 26(7), 1782-1785. doi:10.1519/jsc.0b013e31824e1211
- Huang, J. S., Pietrosimone, B. G., Ingersoll, C. D., Weltman, A. L., & Saliba, S. A. (2011). Sling exercise and traditional warm-up have similar effects on the velocity

and accuracy of throwing. *Journal of Strength and Conditioning Research*, 25(6), 1673-1679. doi:10.1519/jsc.0b013e3181da7845

Kibler, W. B., Press, J., & Sciascia, A. (2006). The role of core stability in athletic function. *Sports Medicine*, 36(3), 189-198. doi:10.2165/00007256-200636030-00001

Kung, S. M., Shultz, S. P., Kontaxis, A., Kraszewski, A. P., Gibbons, M. W., Backus, S. I., ... Hillstrom, H. J. (2017). Changes in lower extremity kinematics and temporal parameters of adolescent baseball pitchers during an extended pitching bout. *The American Journal of Sports Medicine*, 45(5), 1179-1186. doi:10.1177/0363546516687289

Lehman, G., Drinkwater, E. J., & Behm, D. G. (2013). Correlation of throwing velocity to the results of lower-body field tests in male college baseball players. *Journal of Strength and Conditioning Research*, 27(4), 902-908. doi:10.1519/jsc.0b013e3182606c79

MacWilliams, B. A., Choi, T., Perezous, M. K., Chao, E. Y., & McFarland, E. G. (1998). Characteristic ground-reaction forces in baseball pitching. *The American Journal of Sports Medicine*, 26(1), 66-71. doi:10.1177/03635465980260014101

Matsuo, T., Escamilla, R. F., Fleisig, G. S., Barrentine, S. W., & Andrews, J. R. (2001). Comparison of kinematic and temporal parameters between different pitch velocity groups. *Journal of Applied Biomechanics*, 17(1), 1-13. doi:10.1123/jab.17.1.1

McCrary, J. M., Ackermann, B. J., & Halaki, M. (2015). A systematic review of the effects of upper body warm-up on performance and injury. *British Journal of Sports Medicine*, 49(14), 935-942. doi:10.1136/bjsports-2014-094228

Melugin, H. P., Leafblad, N. D., Camp, C. L., & Conte, S. (2018). Injury prevention in baseball: from youth to the pros. *Current Reviews in Musculoskeletal Medicine*, 11(1), 26-34. doi:10.1007/s12178-018-9456-5

Montoya, B. S., Brown, L. E., Coburn, J. W., & Zinder, S. M. (2009). Effect of warm-up with different weighted bats on normal baseball bat velocity. *Journal of Strength and Conditioning Research*, 23(5), 1566-1569. doi:10.1519/jsc.0b013e3181a3929e

Newton, R. U., Murphy, A. J., Humphries, B. J., Wilson, G. J., Kraemer, W. J., & Häkkinen, K. (1997). Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *European Journal of Applied Physiology*, 75(4), 333-342. doi:10.1007/s004210050169

Okoroha, K. R., Meldau, J. E., Lizzio, V. A., Meta, F., Stephens, J. P., Moutzouros, V., & Makhni, E. C. (2018). Effect of fatigue on medial elbow torque in baseball pitchers: a simulated game analysis. *The American Journal of Sports Medicine*, 46(10), 2509-2513. doi:10.1177/0363546518782451

- Oliver, G. D., Weimar, W. H., & Plummer, H. A. (2015). Gluteus medius and scapula muscle activations in youth baseball pitchers. *Journal of Strength and Conditioning Research*, 29(6), 1494-1499. doi:10.1519/jsc.0000000000000797
- Olsen, S. J., Fleisig, G. S., Dun, S., Loftice, J., & Andrews, J. R. (2006). Risk factors for shoulder and elbow injuries in adolescent baseball pitchers. *The American Journal of Sports Medicine*, 34(6), 905-912. doi:10.1177/0363546505284188
- Oyama, S., Yu, B., Blackburn, J. T., Padua, D. A., Li, L., & Myers, J. B. (2014). Improper trunk rotation sequence is associated with increased maximal shoulder external rotation angle and shoulder joint force in high school baseball pitchers. *The American Journal of Sports Medicine*, 42(9), 2089-2094. doi:10.1177/0363546514536871
- Pitcher's mound. (2007, October 12). Retrieved from https://www.baseball-reference.com/bullpen/pitcher%27s_mound
- Plummer, H. A., & Oliver, G. D. (2014). The relationship between gluteal muscle activation and throwing kinematics in baseball and softball catchers. *Journal of Strength and Conditioning Research*, 28(1), 87-96. doi:10.1519/jsc.0b013e318295d80f
- Post, E. G., Laudner, K. G., McLoda, T. A., Wong, R., & Meister, K. (2015). Correlation of shoulder and elbow kinetics with ball velocity in collegiate baseball pitchers. *Journal of Athletic Training*, 50(6), 629-633. doi:10.4085/1062-6040-50.1.06
- Raeder, C., Fernandez-Fernandez, J., & Ferrauti, A. (2015). Effects of six weeks of medicine ball training on throwing velocity, throwing precision, and isokinetic strength of shoulder rotators in female handball players. *Journal of Strength and Conditioning Research*, 29(7), 1904-1914. doi:10.1519/jsc.0000000000000847
- Reinold, M. M., Wilk, K. E., Macrina, L. C., Sheheane, C., Dun, S., Fleisig, G. S., ... Andrews, J. R. (2008). Changes in shoulder and elbow passive range of motion after pitching in professional baseball players. *The American Journal of Sports Medicine*, 36(3), 523-527. doi:10.1177/0363546507308935
- Reyes, G. F., & Dolny, D. (2009). Acute effects of various weighted bat warm-up protocols on bat velocity. *Journal of Strength and Conditioning Research*, 23(7), 2114-2118. doi:10.1519/jsc.0b013e3181b3dd32
- Robbins, D. W. (2005). Postactivation potentiation and its practical applicability: a brief review. *The Journal of Strength and Conditioning Research*, 19(2), 453. doi:10.1519/r-14653.1
- Sciascia, A., Thigpen, C., Namdari, S., & Baldwin, K. (2012). Kinetic chain abnormalities in the athletic shoulder. *Sports Medicine and Arthroscopy Review*, 20(1), 16-21. doi:10.1097/jsa.0b013e31823a021f

- Seroyer, S. T., Nho, S. J., Bach, B. R., Bush-Joseph, C. A., Nicholson, G. P., & Romeo, A. A. (2009). Shoulder pain in the overhead throwing athlete. *Sports Health: A Multidisciplinary Approach*, 1(2), 108-120. doi:10.1177/1941738108331199
- Seroyer, S. T., Nho, S. J., Bach, B. R., Bush-Joseph, C. A., Nicholson, G. P., & Romeo, A. A. (2010). The kinetic chain in overhand pitching: its potential role for performance enhancement and injury prevention. *Sports Health: A Multidisciplinary Approach*, 2(2), 135-146. doi:10.1177/1941738110362656
- Southard, D., & Groomer, L. (2003). Warm-up with baseball bats of varying moments of inertia: effect on bat velocity and swing pattern. *Research Quarterly for Exercise and Sport*, 74(3), 270-276. doi:10.1080/02701367.2003.10609091
- Stodden, D. F., Fleisig, G. S., McLean, S. P., Lyman, S. L., & Andrews, J. R. (2001). Relationship of pelvis and upper torso kinematics to pitched baseball velocity. *Journal of Applied Biomechanics*, 17(2), 164-172. doi:10.1123/jab.17.2.164
- Stodden, D. F., Fleisig, G. S., McLean, S. P., & Andrews, J. R. (2005). Relationship of biomechanical factors to baseball pitching velocity: within pitcher variation. *Journal of Applied Biomechanics*, 21(1), 44-56. doi:10.1123/jab.21.1.44
- Stodden, D. F., Campbell, B. M., & Moyer, T. M. (2008). Comparison of trunk kinematics in trunk training exercises and throwing. *Journal of Strength and Conditioning Research*, 22(1), 112-118. doi:10.1519/jsc.0b013e31815f2a1e
- Szymanski, D. J., Beiser, E. J., Bassett, K. E., Till, M. E., Medlin, G. L., Beam, J. R., & DeRenne, C. (2011). Effect of various warm-up devices on bat velocity of intercollegiate baseball players. *Journal of Strength and Conditioning Research*, 25(2), 287-292. doi:10.1519/jsc.0b013e318202e31e
- Szymanski, D. J., Szymanski, J. M., Bradford, T. J., Schade, R. L., & Pascoe, D. D. (2007). Effect of twelve weeks of medicine ball training on high school baseball players. *Journal of Strength and Conditioning Research*, 21(3), 894-901. doi:10.1519/00124278-200708000-00041
- Thacker, S. B., Gilchrist, J., Stroup, D. F., & Kimsey, C. D. (2004). The impact of stretching on sports injury risk: a systematic review of the literature. *Medicine & Science in Sports & Exercise*, 36(3), 371-378. doi:10.1249/01.mss.0000117134.83018.f7
- Urbini, M., Fleisig, G. S., Abebe, A., & Andrews, J. R. (2012). Associations between timing in the baseball pitch and shoulder kinetics, elbow kinetics, and ball speed. *The American Journal of Sports Medicine*, 41(2), 336-342. doi:10.1177/0363546512467952
- Van Trigt, B., Schallig, W., Van der Graaff, E., Hoozemans, M., & Veeger, D. (2018). Knee angle and stride length in association with ball speed in youth baseball pitchers. *Sports*, 6(2), 51. doi:10.3390/sports6020051

- Werner, S. L., Suri, M., Guido, J. A., Meister, K., & Jones, D. G. (2008). Relationships between ball velocity and throwing mechanics in collegiate baseball pitchers. *Journal of Shoulder and Elbow Surgery*, 17(6), 905-908. doi:10.1016/j.jse.2008.04.002
- Wilcox, J., Larson, R., Brochu, K. M., & Faigenbaum, A. D. (2006). Acute explosive-force movements enhance bench-press performance in athletic men. *International Journal of Sports Physiology and Performance*, 1(3), 261-269. doi:10.1123/ijsp.1.3.261
- Wilk, K. E., Macrina, L. C., & Arrigo, C. (2012). Passive range of motion characteristics in the overhead baseball pitcher and their implications for rehabilitation. *Clinical Orthopaedics and Related Research®*, 470(6), 1586-1594. doi:10.1007/s11999-012-2265-z
- Wilk, K. E., Meister, K., & Andrews, J. R. (2002). Current concepts in the rehabilitation of the overhead throwing athlete. *The American Journal of Sports Medicine*, 30(1), 136-151. doi:10.1177/03635465020300011201
- Williams, C. C., Gdovin, J. R., Wilson, S. J., Cazas-Moreno, V. L., Eason, J. D., Hoke, E. L., ... Garner, J. C. (2019). The effects of various weighted implements on baseball swing kinematics in collegiate baseball players. *Journal of Strength and Conditioning Research*, 33(5), 1347-1353. doi:10.1519/jsc.0000000000002020