Relationship between Kinetics of Countermovement Jump and Proximal Mechanics of Collegiate Baseball Pitching

Motoki Sakurai

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RELATIONSHIP BETWEEN KINETICS OF COUNTERMOVEMENT JUMP AND PROXIMAL MECHANICS OF COLLEGIATE BASEBALL PITCHING

by

Motoki Sakurai, B.S.

A Thesis Presented in Partial Fulfillment Of the Requirements for the Degree Master of Science in Kinesiology

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ABSTRACT

Purpose: To identify how countermovement jump (CMJ) kinetics influence kinematics and momentum of the baseball pitching motion with a focus on lower body and proximal movement. Methods: Nineteen Division I collegiate pitchers (age = 19.9 ± 1.5 years; height = 1.86 ± 0.06 m; weight = 90.7 ± 13.8 kg) performed a bilateral CMJ test and threw 5 strike fastballs from the stretch with a slide step on a custom-made pitching mound built for a laboratory setting. A 3D motion capture system tracked whole-body kinematics at 240 Hz from 29 reflective markers. Two force plates recorded ground reaction forces (GRFs) from each leg at 1040 Hz during both jump test and pitching captures. A one-way ANOVA separating high and low fastball velocity groups by an athlete’s median performance identified differences in pitching mechanics and jump kinetic variables. Meaningful differences between the variables were determined by Cohen’s d effect size with 95% confidence intervals. The same statistical calculations were repeated to identify differences in pitching mechanics and jump kinetic variables between two groups, split based on the medians of pitchers’ total linear momentum in anterior-posterior direction.

Results: High throwing velocity group showed a significant increase in absolute peak power ($p < 0.01$) and higher GRF ($p < 0.01$) than low throwing velocity group for CMJ. The high momentum group showed a significant increase in concentric impulse ($p < 0.05$) than the low momentum group. All of the pitching mechanics variables except for the momentum profiles did not show significant differences in both ANOVA tests.

Conclusions: Key findings suggest the importance of lower body power, as CMJ data has
the potential to separate throwing velocity ability in pitchers, coupled with greater total mediolateral and transverse momentum with higher peak power in the CMJ.

**Keywords:** baseball pitching, countermovement jump, fastball velocity, ground reaction forces
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Author _____________________________

Date ______________________________

v
# TABLE OF CONTENTS

ABSTRACT .................................................................................................................. III

APPROVAL FOR SCHOLARY DISSEMINATION ..................................................... V

LIST OF TABLES ........................................................................................................ vii

LIST OF FIGURES ...................................................................................................... viii

ACKNOWLEDGMENTS ............................................................................................. ix

KEY TO ABBREVIATIONS ....................................................................................... X

CHAPTER 1 INTRODUCTION .................................................................................... 11

CHAPTER 2 REVIEW OF LITERATURE .................................................................. 14

  2.1 Background and Significance Overview ......................................................... 14
  2.2 Throwing Arm Mechanics and Pitching ......................................................... 15
  2.3 Trunk Mechanics and Pitching ..................................................................... 18
  2.4 Lower Body Mechanics and Pitching ............................................................. 21
  2.5 Lower Body Power Testing and Pitching ...................................................... 25
  2.6 Overall Conclusion ....................................................................................... 27

CHAPTER 3 METHOD .............................................................................................. 29

  3.1 Participants ................................................................................................... 29
  3.2 Experimental Design .................................................................................... 29
  3.3 Data Collection ............................................................................................. 30
  3.4 Statistical Analysis ....................................................................................... 37

CHAPTER 4 RESULTS ............................................................................................. 39

CHAPTER 5 DISCUSSION ......................................................................................... 49

CHAPTER 6 CONCLUSION ...................................................................................... 56

REFERENCES ........................................................................................................... 57

APPENDICES .......................................................................................................... 64

  Appendix A ......................................................................................................... 64
  Appendix B ......................................................................................................... 65
LIST OF TABLES

Table 3-1. Marker set placed on participants for pitching test ........................................33
Table 3-2. Variables for pitching motion capture ..................................................................36
Table 3-3. Variables for jump trials ..................................................................................37
Table 4-1. Pitching mechanics and jump variables across throwing velocity (Fast vs. Slow) ....................................................................................................................42
Table 4-2. Height, body mass, and lean body mass across throwing velocity (Fast vs. Slow) ..........................................................................................................................42
Table 4-3. Pitching mechanics and jump variables across total linear momentum in AP direction (High Momentum vs. Low Momentum) .......................................................43
Table 4-4. Height, body mass, and lean body mass across AP linear momentum (High vs. Low) ..................................................................................................................................43
LIST OF FIGURES

Figure 2-1. Six phases of the pitching cycle. ...............................................................16
Figure 2-2. Separation angle between torso and pelvis. ............................................20
Figure 2-3. Lateral trunk tilt (left) and forward trunk tilt (right). ...............................21
Figure 3-1. Laboratory setting for pitching motion capture test ..................................30
Figure 3-2. A whole-body marker set used for the pitching test ...............................32
Figure 3-3. Pitching cycle starting with peak knee height (PKH) followed by stride foot
          contact (SFC), maximum shoulder external rotation (MER), and ending with
          ball release (BR) ..................................................................................................34
Figure 4-1. Force-time curve for fast and slow throwing velocity groups recorded in the
          CMJ assessment ..................................................................................................44
Figure 4-2. Force-time curve normalized by body weight for fast and slow throwing
          velocity groups recorded in the CMJ assessment ...........................................45
Figure 4-3. Participants’ average profile of total linear momentum in the anterior-
          posterior (AP) direction throughout the pitching cycle ......................................46
Figure 4-4. Each group’s average profile of total linear momentum in the mediolateral
          (ML) direction throughout the pitching cycle ..................................................47
Figure 4-5. Participant’s average profile of total transverse angular momentum
          throughout the pitching cycle ............................................................................48
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# KEY TO ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AP</td>
<td>Anterior-posterior</td>
</tr>
<tr>
<td>BR</td>
<td>Ball Release</td>
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<td>CI</td>
<td>Concentric Impulse</td>
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<tr>
<td>CMJ</td>
<td>Countermovement Jump</td>
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<tr>
<td>E-RFD</td>
<td>Eccentric Rate of Force Development</td>
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<td>GRF</td>
<td>Ground Reaction Force</td>
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<tr>
<td>MER</td>
<td>Maximum Shoulder External Rotation</td>
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<tr>
<td>MIR</td>
<td>Maximum shoulder Internal Rotation</td>
</tr>
<tr>
<td>ML</td>
<td>Mediolateral</td>
</tr>
<tr>
<td>PKH</td>
<td>Peak Knee Height</td>
</tr>
<tr>
<td>RSImod</td>
<td>Reactive Strength Index Modified</td>
</tr>
<tr>
<td>SFC</td>
<td>Stride Foot Contact</td>
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<tr>
<td>SLAP</td>
<td>Superior Labrum Anterior to Posterior lesions</td>
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<tr>
<td>UCL</td>
<td>Ulnar Collateral Ligament injury</td>
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<td>VJ</td>
<td>Vertical Jump</td>
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CHAPTER 1
INTRODUCTION

Baseball pitching is an explosive, high-demand athletic skill that involves fine coordination of the entire body (Chelly et al., 2010; Lachowetz et al., 1998). Mechanical energy is transferred from the lower body to upper body and eventually reaches the throwing hand at the ball release (Fleisig et al., 1996). The force transfer through sequential body segments, defined as the kinetic chain, provides the rationale in studying the role of lower body mechanics in baseball pitching (Howenstein et al., 2020; Ramsey et al., 2014; Ramsey & Crotin, 2016).

Lower body mechanics in the pitching cycle may indirectly impact pitching performance due to linkage with trunk mechanics and will strongly affect throwing velocity and stress experienced on the throwing arm (Aguinaldo et al., 2007; Aguinaldo & Escamilla, 2019; Luera et al., 2018; Oliver & Keeley, 2010). Recent studies have reported that pitchers who were able to throw a baseball at higher velocity showed greater peak angular velocity of the trunk and pelvis rotations, later onset of the trunk and pelvis rotations, and greater time lag of the trunk reaching peak angular velocity after the pelvis reached its peak angular velocity (Aguinaldo & Escamilla, 2019; Luera et al., 2018; Urbin et al., 2013; van der Graaff et al., 2018). These variables listed above denote effective mechanics of the trunk and ensure efficient momentum transfer from the lower body to the throwing arm. Effective trunk mechanics can be achieved by powerful lower body mechanics which generate greater linear momentum in the anterior-posterior (AP)
direction (movement towards home plate) and angular momentum in the transverse plane (plane of movement that describes rotation towards first base for right-handed pitcher going from frontal plane to squaring up to home plate upon stride foot contact) (Ramsey et al., 2014; Ramsey & Crotin, 2016). Powerful lower body mechanics also may lower the risk of throwing-related injuries. It promotes greater amount of momentum transfer to the throwing arm via the trunk linearly, reduces trunk momentum relative to the arm rotationally, and can create better mechanical efficiency which results in higher ratios of pitching velocity to throwing arm torques (Aguinaldo & Escamilla, 2019; Howenstein et al., 2020; Ramsey et al., 2014; Ramsey & Crotin, 2016). Therefore, given that lower body power improves mechanical efficiency of the kinetic chain, exploration of jump-related profiles in association to biomechanics may prove to be important in reducing throwing arm injuries (Mayberry et al., 2020).

It has been demonstrated that less powerful force development patterns exhibited by the countermovement jump (CMJ) are associated with throwing-related injury history in baseball pitchers (Mayberry et al., 2020). A CMJ test is a relatively quick, valid, and reliable field test which has been widely used by many Major League Baseball (MLB) teams to measure players’ physical performance (Hoffman et al., 2009; Mangine et al., 2013). This simplicity makes the CMJ test possible for regular testing to assess for future injury risk (Mayberry et al., 2020). However, a limitation of the previously mentioned research is that it did not identify kinematic and kinetic variables, which are two areas of biomechanics that deal with the motion and effects of forces upon the body, in the pitching cycle that could be impaired by having reduced lower body power. Statistically significant biomechanical correlations between lower body strength and pitching mechanics were not
identified in the Mayberry et al. (2020) study. Thus, more research needs to be conducted to augment the literature regarding relationships between the kinetic parameters in CMJ and baseball pitching mechanics.

The purpose of this study was to identify how kinetic data measured by force plates in CMJ influences kinematics and momentum of the baseball pitching motion with a focus on lower body and trunk movement. It was hypothesized that pitchers who have more lower body power in jumping would have similar greater lower body power in pitching (product of angular velocity and moment of force at a joint), higher angular velocities of the pelvis and trunk, and a sequential pattern of the pelvis reaching peak angular velocity before that of the trunk. Similarly, it was hypothesized that those pitchers that jump more powerfully will exhibit greater overall linear momentum in the AP direction and demonstrate lesser total body angular momentum in the transverse plane respectively.
CHAPTER 2
REVIEW OF LITERATURE

2.1 Background and Significance Overview

Throwing arm injuries are trending at higher rates at present across all levels of baseball competition (Conte et al., 2016; Erickson et al., 2015). This has led to a significant increase in biomechanical studies using high-speed 3D motion analysis to better understand pitching mechanics with the majority of these biomechanical pitching studies focusing on the upper body and trunk motion (Aguinaldo et al., 2007; Matsuo et al., 2006; Milewski et al., 2012; Oliver & Keeley, 2010). Recent studies have also found that lower body mechanics during pitching influences both risk of injury and pitching performance (Ramsey et al., 2014; Ramsey & Crotin, 2016; Smidebush et al., 2019). Many of these biomechanical studies examined kinematic and kinetic variables and provided rationales regarding optimal pitching mechanics, injury risk factors, and practical applications to prevent throwing-related injuries (Escamilla et al., 2018; Fleisig et al., 1996; Oyama, 2012). It has been suggested that throwing velocity is strongly correlated with both upper body and lower body strength (Chelly et al., 2010; Hermassi et al., 2015; Lachowetz et al., 1998; Szymanski et al., 2021) and field testing has been used by professional and collegiate baseball strength and conditioning coaches and teams to measure their players’ physical strength, power, speed, and agility (Hoffman et al., 2009; Mangine et al., 2013; Szymanski et al., 2021). Although previous research studies revealed that a lower body power test
correlated with throwing velocity of overhead athletes (Chelly et al., 2010; Szymanski et al., 2020), more research is warranted to better understand relationships between baseball pitching mechanics and lower body power measured by field testing.

2.2 Throwing Arm Mechanics and Pitching

Pitching-related injury and pitching performance are deeply connected with one another, and kinematic and kinetic variables have been taken into consideration in many biomechanical studies to assess risk between throwing-related injury and pitching performance (Aguinaldo & Escamilla, 2019; Cohen et al., 2019; Escamilla et al., 1998; Luera et al., 2018). When a pitcher throws a baseball from the mound to home plate, the throwing arm experiences tremendous amount of force loading with rotational movements throughout the pitching cycle, and maximum speeds of the shoulder internal rotation that can range from 7000° to 9000° per second at ball release which occurs within less than 1 second (Sgroi & Zajac, 2018). Therefore, both the shoulder and elbow joints need to tolerate these moments of force to prevent injuries, as stress on the throwing arm will increase as the pitcher throws at higher ball velocity (Slowik et al., 2019).

Fleisig et al. (1999) divided the pitching cycle into six phases (Figure 2-1) consisting of the wind-up phase occurring from the initial position to maximum knee height (MKH), stride phase from MKH to stride foot contact (SFC), arm cocking phase from SFC to maximum shoulder external rotation (MER), arm acceleration phase from MER to ball release (BR), arm deceleration phase from BR to maximum shoulder internal rotation (MIR), and follow-through phase from MIR to the end of the pitching cycle. Increased elbow varus torque, an eccentric, internal rotational torque opposing valgus loads to reduce
the opening of the medial elbow, is associated with increased maximum shoulder external rotation in the delivery (Aguinaldo & Chambers, 2009; Escamilla et al., 2018) and increased elbow extension at peak elbow valgus torque most likely occurring at the arm cocking phase (Aguinaldo & Chambers, 2009). Oyama (2012) described arm-cocking, acceleration, and deceleration phases as time points where high magnitude joint kinetics are experienced at the shoulder and elbow and associated to the ulnar collateral ligament (UCL) injury and superior labrum anterior to posterior (SLAP) lesions.

![Six phases of the pitching cycle](image)

**Figure 2-1**: Six phases of the pitching cycle (Fleisig et al., 1999).

Previous research studies have commonly used throwing velocity as a variable to evaluate pitching performance while kinematic and kinetic variables have also been examined to understand what kind of body mechanics help pitchers to throw at high velocity. Three previous research studies have reported that throwing at higher velocity increases throwing arm kinetics (Cohen et al., 2019; Matsuo et al., 2001; Oliver & Keeley, 2010). Therefore, it has been identified that there is an inherent risk relationship between risk of injury and pitching performance in which risk of injury increases when throwing velocity increases. Maximum shoulder external rotation appears to be a non-modifiable
kinematic outcome resulting from throwing at higher velocity whereby an increased range of motion can increase medial elbow stress (Aguinaldo & Chambers, 2009; Escamilla et al., 2018).

One way in which high level pitchers may be able to alleviate forces experienced at the throwing arm is to have more efficient kinetic chain transfers from ground reaction force (GRF). The kinetic chain describes the momentum transfer through sequential body segments to achieve maximum magnitude in the terminal segment which is the throwing hand for baseball pitching (Fleisig et al., 1996). The kinetic chain for throwing progresses from the legs to the hips, trunk, upper arm, forearm, hand, and finally to the ball (Fleisig et al., 1996). Therefore, the kinetic chain may help to reduce excessive stress on the throwing arm and previous studies investigating trunk, pelvis, and lower body mechanics for baseball pitching have examined how the motions of these body parts influenced forces experienced at the shoulder and elbow joints during pitching motion (Aguinaldo et al., 2007; Aguinaldo & Chambers, 2009).

Section Summary

Mechanical loading throughout the pitching cycle can stress throwing arm joints. A variety of throwing-related arm injuries are associated with elbow valgus, rotator cuff, and labrum loads that overwhelm the tissues’ ability to withstand tension. More efficient momentum transfer about the kinetic chain may be a solution to prevent elevated force applications and promote an efficient delivery from GRF input to the throwing arm.
2.3 Trunk Mechanics and Pitching

Trunk mechanics are one of the most commonly studied sequential body motions in the kinetic chain for baseball throwing because they show strong correlations with throwing velocity and force loading on the throwing arm. Howenstein et al. (2019) reported that energy flow into the arm from the trunk showed the strongest correlation to throwing velocity among all energy flow variables including energy flow into pelvis, trunk, arm, upper arm, forearm, and hand. Energy flow analysis is a relatively new type of segment power analysis (product of angular and linear velocity and force exerted on a segment) that quantifies how energy is generated and transferred among body segments (Howenstein et al., 2019). Considering these results, generating a large amount of force combined with velocity at the trunk transfers greater energy to the arm that may be crucial to increased throwing velocity, as seen in other research (Aguinaldo & Escamilla, 2019; Luera et al., 2018). A recent study reported that the pelvis peak rotation velocities were significantly and positively correlated with throwing fingertip velocity (van der Graaff et al., 2018) and their regression coefficient indicated that a 67 deg·s⁻¹ increase in peak pelvis rotation velocity would result in 0.45 m·s⁻¹ increase in fingertip velocity. This calculation is consistent with Cohen et al. (2019) who identified 100 deg·s⁻¹ increase over the average maximum rotational velocity of the trunk would result in 0.70 m·s⁻¹ increase in throwing velocity.

Timing of the onset of trunk rotation has been shown to strongly influence both performance enhancement and injury prevention in baseball pitching. Previous studies reported that late onset of trunk rotation in the pitching cycle contributed to throwing higher velocity fastballs and reduced maximum elbow varus torque (Aguinaldo & Escamilla,
On the other hand, the onset of pelvis rotation needs to occur early in the pitching cycle, so that a greater angle difference between pelvis and trunk (i.e., separation angle) can be made at SFC (Figure 2-2). Luera et al. (2018) reported that a significantly greater separation angle was seen at SFC in professional pitchers compared to high school cohort. In terms of timing of segment rotation, the time interval between the peak rotation velocity of the pelvis and the peak rotation velocity of the trunk, defined as “separation time”, is another variable that shows a strong correlation with throwing velocity (Urbin et al., 2013; van der Graaff et al., 2018). van der Graaff et al. (2018) reported that the separation time showed a strong correlation with throwing velocity when the emphasis is put on within-subject variation while between-subject variation would not show the association between the separation time and throwing velocity. Their study observed the causal relationship between the two variables by focusing on the comparison of subject’s data before and after 19-week baseball practice period. In addition, professional pitchers exhibited a similar normalized elbow varus torque to high school pitchers while professionals were able to throw significantly higher velocity balls than the high school cohort (Aguinaldo & Escamilla, 2019; Luera et al., 2018). The authors of these articles concluded that these differences between professional and high school pitchers were attributed to the differences in power output from the trunk which was observed in both studies. Aguinaldo & Escamilla (2019) also described that high school pitchers produced comparable normalized elbow valgus moments due to early trunk rotation albeit lower pitching output (i.e., ball speed). This less efficient pitching pattern increases the risk of UCL injuries which has been increasing in
high school pitchers over the past two decades (Conte et al., 2016; Erickson et al., 2015; Fleisig et al., 2009).

Figure 2-2: Separation angle between trunk and pelvis (Crotin, 2013).

Mixed results have been seen focusing on the effect of trunk angle during baseball pitching and how it influences throwing velocity and risk of injury (Escamilla et al., 2018). Escamilla et al. (2018) found non-significant, but 10% greater elbow varus torque with overhand pitchers with significantly greater trunk forward tilt and contralateral tilt angles (Figure 2-3) than side arm pitchers. Matsuo et al. (2001) reported that a group who pitched higher fastball velocity showed greater forward trunk tilt than another group who pitched lower fastball velocity fastball. These results are consistent with other studies (Oliver & Keeley, 2010; Ramsey et al., 2014). On the other hand, Luera et al. (2018) did not find any significant differences in lateral trunk flexion and forward trunk tilt between professional and high school baseball pitchers despite the differences in throwing velocity and stress on the throwing arm while Aguinaldo & Chambers (2009) reported that pitchers who showed
greater contralateral trunk lean had less elbow valgus torque during the pitching motion. Considering these results, how trunk angles influence pitching performance remains unclear and further research is warranted to understand this complex relationship.

Figure 2-3: Lateral trunk tilt (left) and forward trunk tilt (right) (Escamilla et al., 2018).

Section Summary

Trunk and pelvis mechanics strongly impact the throwing velocity and stress at the throwing arm. It may be crucial to generate large, lower body forces combined with greater angular velocity of the trunk and pelvis for effective transfer to the throwing arm that can allow a pitcher to throw a ball at high velocity and mitigate the stress on the arm. Late onset of trunk rotation and greater separation time between trunk and pelvis rotation may also be beneficial to manage joint loads in throwing without affecting throwing velocity.

2.4 Lower Body Mechanics and Pitching

Previous studies investigating lower body mechanics typically use force plates associated to 3D motion analysis to collect kinematic and kinetic data of lower body to
then identify the forces placed on the throwing arm and/or throwing velocity. MacWilliams et al. (1998) is the first study that examined the GRF patterns of each leg (i.e., drive and stride legs) throughout the pitching cycle and reported that GRFs were primarily concentrated within the direction of the intended throw and the vertical axis. Lateral forces (i.e., towards the direction of the first and third bases) were small and negligible accounting for less than 10% of resultant force (i.e., vector summation of three force components including AP direction, ML direction, and vertical direction) throughout the pitching cycle (MacWilliams et al., 1998). While the majority of studies using force plates have used peak GRF as an independent variable (Kageyama et al., 2015; MacWilliams et al., 1998), GRF impulse (i.e., summation of force over time) may be a better variable for baseball pitching analysis because it provides information about the overall profile of the force-time curve (Howenstein et al., 2020). It enables researchers to provide insight regarding how the body’s momentum changed throughout the pitching cycle including acceleration and deceleration of the body (Aguinaldo & Escamilla, 2019; Howenstein et al., 2020). A recent research article using energy flow analysis identified that GRF impulse highly or moderately correlated with energy flow into all segments including pelvis, trunk, and arm for both drive and stride legs while peak GRF moderately correlated with only the pelvis and trunk for the drive leg and trunk and arm for the stride leg (Howenstein et al., 2020). Moreover, the results of this study indicate that braking kinetics of the stride leg may be crucial to create rotational moments and transferring the mechanical power into the throwing arm from the trunk because peak braking GRF and GRF impulse of the stride leg both moderately correlated with segment power (i.e., product of net joint moments and
segment angular velocities) of energy flow from the trunk into the arm (Howenstein et al., 2020).

Similarly, momentum studies investigated the transfer of segment velocities through the kinetic chain, a product of the segment mass and its velocity of the motion according to the global coordinate system (Ramsey et al., 2014, Ramsey & Crotin, 2016). Momentum is first generated by the drive leg and eventually transitioned to the throwing hand in baseball pitching (Ramsey et al., 2014). The authors of this study defined momentum compensation ratios indicating throwing arm momentum as a proportion of the total body momentum. The researchers incorporated this proportion to better understand the relationship of how fast the throwing arm segment moves with respect to the largest mass, which was reported as the trunk (Ramsey et al., 2014). All momentums are impacted by forces generated by other body parts including legs and trunk. Ramsey et al. (2014) reported that the extended stride length during pitching resulted in the increase in both total body and throwing arm linear momentums, specifically in the AP direction (forward toward home plate) which decreased the throwing arm momentum compensation ratio in transverse plane. These results indicate that having relatively longer stride length (+25% increase in pitcher’s desired stride length in meters) may be better than having shorter stride length (25% decrease in pitcher’s desired stride length in meters) in order to alleviate the stress on the throwing arm which may lead to reduced risk of injury (Oliver & Keeley, 2010; Ramsey et al., 2014). Increased stride length is also associated with altered timing of hallmark events such as SFC and MER in the pitching cycle. Delayed onset of stride foot contact caused by greater stride length allowed pitchers to have a longer duration of single support phase and promoted forward momentum (Ramsey et al., 2014). After SFC,
total body momentum shifted laterally and greater magnitudes were observed with longer strides in the frontal plane (Ramsey et al., 2014). In the second component of their two-part series study, they investigated the effect of stride length on an angular momentum response during pitching and revealed that longer stride length achieved greater total body angular momentum particularly in the intended throwing direction due to flexion of the trunk, which is consistent with the results in the linear momentum study (Ramsey & Crotin, 2016). Shorter stride length increased transverse trunk momentum before throwing arm acceleration that may elicit undesirable momentum exchange between the trunk and throwing arm by increasing the risk of hyper-angulation of the humerus in the approach of MER of the shoulder (Ramsey & Crotin, 2016). The authors mentioned that transverse momentum analyses have the potential to provide beneficial information regarding the risk of throwing-related arm injuries (Ramsey & Crotin, 2016). Considering the results seen in the two momentum studies, anterior and transverse momentum proved to be particularly impacted by stride length differences.

Section Summary

Variables that track the change in kinetic profiles throughout the pitching cycle such as GRF impulse may provide more beneficial information for baseball pitching than the others that provide data for a specific time point such as peak GRF. Also, linear momentum in the AP direction and transverse plane should be examined relative to lower body power to further understand how it influences pitching mechanics in relation to throwing velocity and potential stress experienced at the throwing arm.
2.5 Lower Body Power Testing and Pitching

Although previous studies have identified that the lower body force output through the pitching cycle showed a significant, positive correlation with throwing velocity (Howenstein et al., 2020; Kageyama et al., 2015; MacWilliams et al., 1998), not many investigations have been conducted on the relationships between lower body performance tests and lower body mechanics for baseball pitching. It remains unclear how well lower body performance field tests correlate with pitching performance because, at this time, MLB teams have only reported how physical performance tests relate to offensive statistics of position players (Hoffman et al., 2009).

The CMJ is known as one of the most reliable and valid forms of jump tests for assessing athletic performance (Mayberry et al., 2020) and has been used by previous researchers to collect physical performance data of high school, college, and professional baseball players (Hoffman et al., 2009; Mangine et al., 2013; Mayberry et al., 2020; Szymanski et al., 2010). Subjects in the study by Hoffman et al. (2009) were 343 position players and their results showed small to moderate correlations between lower body power output calculated from vertical jump height and body mass and associated hitting performance (e.g., home runs, total bases, slugging percentage). For pitchers, it has been reported that vertical jump estimated peak power peaked in their early 20s and vertical jump estimated mean power peaked in the group aged between 29-31. Both of these vertical jump estimated power values started to decline when players reached their 30s (Mangine et al., 2013). In future work, these results may indicate a greater relationship between lower body power and throwing velocity (Chelly et al., 2010), as players who are able to play into their 30s potentially could rely more on range of motion adaptations to load the
shoulder joint amid a reduction in lower body power (Mangine et al., 2013). A recent research article measuring professional baseball pitchers’ CMJ reported that players who showed lower rate of force development during the eccentric phase of the jump (i.e., descending phase of CMJ) and less balanced force output during the concentric phase (i.e., ascending phase from the bottom position to take-off) of their jump tend to have higher rate of elbow injuries during their career (Mayberry et al., 2020). More specifically, low rates of force development during the eccentric phase relative to high concentric vertical impulse coupled with low average vertical concentric impulse, and low concentric vertical impulse coupled with high average vertical concentric impulse were associated with higher risk of elbow injury while shoulder injury rates did not correlate with these CMJ test variables (Mayberry et al., 2020). To the best of our knowledge, this is the only study that has investigated the relationships between the results of lower body power testing and the risk of throwing-related arm injuries. In other throwing sports, handball throwing velocity moderately correlated with lower body power seen in cycle ergometer tests (Chelly et al., 2010). Considering these results, it may be important for pitchers to have effective alactic metabolism and lower body power. A highly conditioned alactic system refers to efficient, creatine-phosphate driven metabolism that can assist pitchers in their ability to repeat explosive lower body power and may help to prevent elbow injuries while sustaining fastball velocity over the course of games. However, these studies were limited by not identifying kinematic and kinetic variables in the throwing cycle that differed according to varying strength levels for the lower body and how lower body power tests correlate to throwing performance that is typically expressed by throwing velocity. Investigation of these relationships provide beneficial insights for baseball coaches and pitchers because
they would be able to know potential pitching performance implications based on field assessment results that may infer coaching directives.

Section Summary

CMJ tests may be a valid and reliable assessment to know a pitcher’s potential for improving pitching performance and minimizing injury risk. However, little investigation has been conducted on the relationships between jump performance and baseball pitching mechanics. Force output patterns in CMJ are considered to reflect lower body strength and power which may be important for pitchers to throw more efficiently and consistently.

2.6 Overall Conclusions

Previous biomechanical studies for baseball pitching have identified whole body kinematics and kinetics that enhance pitching performance and decrease risk of injuries. Although the trunk showed the strongest correlation with power generation in distal segments, enhanced motor control of trunk motion can reduce stress on the throwing arm (Aguinaldo & Escamilla, 2019; Ramsey et al., 2014) while the lower body plays an important role in transferring energy from the pelvis to the trunk, and then transmission of proximal power to the throwing arm (Howenstein et al., 2020; Ramsey & Crotin, 2016). Correlations between overhead throwing velocity and lower body power measured by jump tests (Chelly et al., 2010; Mayberry et al., 2020; Szymanski et al., 2020, 2021) are known, yet more information is needed to gain knowledge regarding how kinematic and/or kinetic variables are impacted by changes in lower body power, as determined by field tests. Further research is needed to identify these relationships to better understand pitching mechanics and the validity and application of jump tests for assessment of baseball
pitchers. The intersection of lower body power testing and biomechanical analysis can play an important role in uniting strength and conditioning, pitching coaches, and biomechanics experts in bringing about advancement in pitching performance and health.
CHAPTER 3

METHOD

3.1 Participants

Nineteen Division I collegiate baseball pitchers (15 right-handed and 4 left-handed; age 19.9 ± 1.5 years; height 1.86 ± 0.06 m; body mass 90.7 ± 13.8 kg) participated in this study after providing written informed consents approved by the Louisiana Tech University institutional review board. All pitchers were considered relatively healthy with no significant bodily injury or had fully recovered from previous injury at the time of testing. Pitchers who had injuries or those who were not medically cleared to participate at time of testing were excluded from this study. Experiments occurred indoors in the Sport and Movement Science Laboratory at Louisiana Tech University.

3.2 Experimental Design

Experiments consisted of two parts, pitching motion capture test and CMJ test. Participants were asked to throw 4-seam fastballs from the stretch with a slide step on a custom-made pitching mound built for a laboratory setting with two embedded force plates (Figure 3-1) after completing a standard rotator cuff program and their own warm-up routine. Only strikes recorded by the ball tracking device (Pitching 2.0, Rapsodo, Missouri, USA) were counted, and participants kept throwing until they recorded 5 strikes. For the CMJ test, participants were asked to perform bilateral CMJs for three trials in a laboratory
setting from two embedded force plates while using a Vertec jump testing device (Vertec Jump Measuring Device, Rogue Fitness HQ, Ohio, USA) to measure jump height. If they completed the test after the third trial, they performed additional CMJs until they failed to jump higher.

![Diagram of laboratory setting for pitching motion capture test](image)

**Figure 3-1:** Laboratory setting for pitching motion capture test.

### 3.3 Data Collection

*Instruments and data collection*

A 12-camera, 3D motion capture system (Miqus M3, Qualisys, Göteborg, Sweden) recorded whole-body kinematics from 29 reflective markers at 240 Hz and two force plates (600 × 900 mm, model 6090-15, Bertec Corp., Columbus, OH, USA) recorded GRFs from each leg at 1040 Hz during both pitching test and CMJ test.
For the pitching test, the markers were placed on subject’s head (RFHD, RBHD, LFHD, and LBHD), upper torso (CLAV, STRN, C7, and T10), pelvis (RASI, RPSI, LASI, and LPSI), right arm (RSHO, RELB, RWRA, RWRB, and RFIN), left arm (LSHO, LELB, glove-1, and glove-5), right leg (RKNE, RANK, RHEE, and RTOE), and left leg (LKNE, LANK, LHEE, and LTOE) as described in Figure 3-2 and Table 3-1. For left-handed participants, the markers for glove were placed on their right hand and the markers for fingers were placed on their left hand. One force plate was placed in front of and in-line with the rubber to record forces from the drive leg and the other force plate was set to the area where participants were expected to land their stride leg foot. Pitching kinematic and kinetic data was collected throughout the pitching cycle starting at PKH where a stride knee reaches the highest position and ending at BR where ball was released from a pitcher’s fingers (Figure 3-3). Both phases were manually identified for each trial by visual inspection of the trajectories of the marker on the pitcher’s stride knee and the ball, respectively. Besides the two hallmark events, SFC occurring after PKH was determined when the stride leg GRF increased to a threshold of 2 N. MER following SFC was identified when pitchers achieved the greatest negative humeral axial rotation.

For the CMJ test, the finger markers were placed on both hands instead of having the glove markers on one of the hands. Participants performed the CMJs while each foot was placed on separate force plates to measure GRFs. The jump height was determined using the Vertec jumping device as the number of vanes displaced above the metal pole and subtracted from the standing reach height. Jump kinematic and kinetic data was collected using the motion capture cameras recording all CMJ trials starting from the initiation of the movement to the landing after making a jump. The instants of
touchdown/takeoff and landing were determined when the vertical GRF increased/decreased to a threshold of 2 N.

**Figure 3-2:** A whole-body marker set used for pitching test.
**Table 3-1:** Marker set placed on participants for pitching test.

<table>
<thead>
<tr>
<th>Location</th>
<th>Marker Set</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>RFHD/LFHD</td>
<td>Forehead</td>
</tr>
<tr>
<td></td>
<td>RBHD/LFHD</td>
<td>Back of the Head</td>
</tr>
<tr>
<td>Torso</td>
<td>C7</td>
<td>7th cervical vertebrae</td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>10th thoracic vertebrae</td>
</tr>
<tr>
<td></td>
<td>CLAV</td>
<td>Clavicle</td>
</tr>
<tr>
<td></td>
<td>STRN</td>
<td>Sternum</td>
</tr>
<tr>
<td>Arm</td>
<td>RSHO/LSHO</td>
<td>Greater tuberosity</td>
</tr>
<tr>
<td></td>
<td>RELB/LELB</td>
<td>Olecranon</td>
</tr>
<tr>
<td></td>
<td>RWRA/LWRA</td>
<td>Ulnar stylus</td>
</tr>
<tr>
<td></td>
<td>RWRB/LWRB</td>
<td>Radial stylus</td>
</tr>
<tr>
<td></td>
<td>RFIN/LFIN</td>
<td>Head of 3rd metacarpal</td>
</tr>
<tr>
<td></td>
<td>glove-1</td>
<td>Glove</td>
</tr>
<tr>
<td></td>
<td>glove-5</td>
<td>Glove</td>
</tr>
<tr>
<td>Pelvis</td>
<td>RASI/LASI</td>
<td>Anterior iliac spines</td>
</tr>
<tr>
<td></td>
<td>RPSI/LPSI</td>
<td>Superior iliac spines</td>
</tr>
<tr>
<td>Leg</td>
<td>RKNE/LKNE</td>
<td>Lateral epicondyle</td>
</tr>
<tr>
<td></td>
<td>RANK/LANK</td>
<td>Lateral malleoli</td>
</tr>
<tr>
<td></td>
<td>RHEE/LHEE</td>
<td>Heel</td>
</tr>
<tr>
<td></td>
<td>RTOE/LTOE</td>
<td>Toe</td>
</tr>
</tbody>
</table>

*Note: RFHD/LFHD = Right/Fixed forehead, RBHD/LFHD = Right Back of the Head, CLAV = Clavicle, STRN = Sternum, RSHO/LSHO = Right/Left Shoulder, RELB/LELB = Right/Left Elbow, RWRA/LWRA = Right/Left Wrist, RWRB/LWRB = Right/Left Wrist, RFIN/LFIN = Right/Left Finger, glove-1 = Glove, glove-5 = Glove, RASI/LASI = Right/Lateral Anterior Iliac Spine, RPSI/LPSI = Right/Lateral Superior Iliac Spine, RKNE/LKNE = Right/Lateral Knee, RANK/LANK = Right/Lateral Ankle, RHEE/LHEE = Right/Lateral Heel, RTOE/LTOE = Right/Lateral Toe.*
Figure 3-3: Pitching cycle starting with peak knee height (PKH) followed by stride foot contact (SFC), maximum shoulder external rotation (MER), and ending with ball release (BR).

Inverse kinematics and dynamics

The inverse kinematics and dynamics were calculated using a 15-segment, 40-degree of freedom (DOF) human model (Qiao, 2021). Segments are the upper and lower torsos, head, hands, feet, upper/lower arms, and legs. Upper and lower torso were connected by a ball-and-socket joint with three DOFs; shoulders, hips, neck, and wrists are ball-and-socket joints; elbows and knees are hinges; ankles have plantar-flexion/extension, inversion/eversion, internal/external rotation; the upper body has another three translational coordinates and three Euler angles in the order of roll, pitch, and rotation relative to the global reference. The anthropometric parameters, i.e., the mass, moments of inertia, COM for each body segment, and the joint location, were determined by allometric scaling of a reference human model (Huston & Passerello, 1982).

The joint angles at each time sample were calculated by using inverse kinematics. The inverse kinematics algorithm iteratively searched for joint angles that minimized a cost function (i.e., the sum of squares of the differences between measured markers and markers calculated from joint angles) (Qiao & Jindrich, 2016). For inverse dynamics, the time series
of joint angles were filtered with a 4th-order zero-lag low-pass Butterworth digital filter at 11 Hz and differentiated to calculate the angular velocities and accelerations. The GRFs and moments from the force plates were low pass filtered at 60 Hz. The net mechanical moments of force \( M(t)_{\text{joint}} \) for all joints were calculated using Kane’s method (Huston & Passerello, 1982). Joint mechanical power \( P(t)_{\text{joint}} \) was calculated as the dot product of instantaneous joint angular velocity and moment vectors. Integrating \( P(t)_{\text{joint}} \) during the landing or takeoff gave the mechanical work. The position of the whole body’s COM was calculated as a weighted average of the COM of each body segment. The magnitude \( v \) and direction \( \theta \) of COM velocity at the instants of landing and takeoff were calculated.

*Variable calculations*

For the pitching test, proximal mechanics were captured for the pelvis and trunk including peak angular velocity, timing differences between peak angular velocities and separation angles at SFC. In addition, total linear momentum in the AP direction (i.e., direction towards home plate from the mound) and the mediolateral (ML) direction (i.e., direction towards first base for right-handed pitcher), and transverse total angular momentum were calculated as described in Table 3-2.

For the CMJ test, variables calculated from kinematics and kinetics data were as follows: absolute peak power, peak power normalized by body mass, eccentric rate of force development (E-RFD), concentric impulse (CI), take off velocity, reactive strength index modified (RSI\text{mod}), and stride leg peak force compensation. Formulas used to calculate them are listed in Table 3-3.
Table 3-2: Variables for pitching motion capture.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk and pelvis peak angular velocity (m·s(^{-1}))</td>
<td>The peak value of (\dot{\theta}) in trunk and pelvis, respectively</td>
</tr>
<tr>
<td>Timing differences in reaching peak angular velocity</td>
<td>Timing of trunk reaching peak angular velocity – Timing of pelvis reaching peak angular velocity</td>
</tr>
<tr>
<td>Separation angle between pelvis and trunk at SFC (º)</td>
<td>Angle of trunk along with transverse plane – angle of pelvis along with transverse plane</td>
</tr>
</tbody>
</table>
| Total body linear momentum in AP direction (kg·m·s\(^{-1}\)) | \(P_x = \sum m_i v_i^x\)  
\(m_i: \) segment mass, \(v_i^x: \) linear velocity in AP |
| Total body linear momentum in ML direction (kg·m·s\(^{-1}\)) | \(P_y = \sum m_i v_i^y\)  
\(v_i^y: \) linear velocity in ML |
| Total body angular momentum in transverse plane (kg·m\(^2\)) | \(L = \begin{pmatrix} L_x \\ L_y \\ L_z \end{pmatrix} = r_{CoM} \times \sum m_i v_{CoM} + \sum L_i'\)  
\(L' = I_{seg} \times \omega\)  
\(I_{seg}: \) segment mass moment of inertia, \(\omega: \) angular velocity, |

### Table 3-3: Variables for jump trials.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute peak power (W)</td>
<td>The peak from a force × velocity</td>
</tr>
<tr>
<td>Normalized peak power (W·kg)</td>
<td>Absolute peak power/Body mass</td>
</tr>
<tr>
<td>Eccentric RFD (N·s⁻¹)</td>
<td>ΔGRF/Time taken from the initiation of the movement to the bottom position where the COM reaches its lowest point and is at 0 velocity</td>
</tr>
<tr>
<td>Concentric impulse (N·s)</td>
<td>ΔGRF × Time taken from the bottom position to take off</td>
</tr>
<tr>
<td>Take off velocity (m·s⁻¹)</td>
<td>Vertical velocity of COM at take-off</td>
</tr>
<tr>
<td>RSImod (m·s⁻¹)</td>
<td>Jump height/contraction time (i.e., duration from the initiation of the movement to take off)</td>
</tr>
<tr>
<td>Stride Leg Peak Force Compensation</td>
<td>(Stride Leg Peak GRF - Drive Leg Peak GRF)/Total Peak GRF</td>
</tr>
</tbody>
</table>

### 3.4 Statistical Analysis

The median of five pitches for each pitching mechanics variables was used to represent a participant’s pitching data. For the CMJ test, a jump trial that showed the highest jump height of all CMJ trials for each participant was used to represent a participant’s jump data and jump kinetic variables were calculated. Two, one-way ANOVA tests were performed to identify differences in proximal pitching mechanics and jump kinetics based on throwing velocity (high throwing velocity group vs. low throwing velocity group) and total linear momentum in the AP direction (high momentum group vs. low momentum group). For both tests, the median of each variable was identified to separate the participants into two groups. The effect sizes for a pooled sample in ANOVAs were reported as $d$. 
All calculations were performed using MATLAB (MathWorks®, Inc., Natick, MA, USA). Statistical comparisons assumed an alpha level of 0.05. All values are represented as mean ± SD.
CHAPTER 4
RESULTS

Table 4-1 shows the mean values for the dependent variables in each group, fast throwing velocity and slow throwing velocity. For the pitching motion capture test, the fast velocity group had significantly higher linear momentum in the ML direction \( (p < .001) \) and higher transverse angular momentum \( (p < .01) \) with small effect sizes for both variables \( (d = 0.33 \text{ and } d = 0.22, \text{ respectively}) \). The linear momentum in the AP direction did not show a significant difference between the two groups \( (p = .06) \), yet a trend emerged as the fast velocity group had greater momentum than the slow velocity group. However, none of variables for proximal mechanics showed significant differences across throwing velocity. For the CMJ test, the fast velocity group showed significantly greater peak vertical GRF than the slow velocity group with a small effect size \( (p = .01, d = 0.22) \). Absolute peak power was also 32% greater in the fast velocity group compared to the slow velocity group with a small effect size \( (p < .001, d = 0.34) \) whereas both the peak GRF and power did not show significant difference when normalized by body weight. Two sample \( t \)-tests were additionally performed to identify if there were significant differences in body height, body mass, and lean body mass between the two groups (Table 4-2). They revealed that the fast velocity group had significantly heavier body mass and lean body mass than the slow velocity group \( (p = .01 \text{ and } p = .01, \text{ respectively}) \). Height did not show significant difference between the two groups \( (p > .05) \). Other CMJ variables such as E-RFD, CI, take-
off velocity, and RSImod did not show significant differences between the two groups. Both groups tended to have a non-significant stride leg dominant force output pattern at the comparable level to each other (fast velocity: 0.009 ± 0.04 vs. slow velocity: 0.01 ± 0.04, p = .77). Figure 4-1 shows the force-time curve for each group during the entire trial of the CMJ starting with the upright standing position and ending with the take-off from the force plates. Figure 4-2 shows the force-time curve while the vertical GRF was normalized by the participants’ body weight.

Table 4-3 shows the mean values for the dependent variables in two groups, high and low total linear momentum in the AP direction. For the pitching test, transverse angular momentum was significantly higher with a trivial effect size in high AP momentum group compared to low AP momentum group (p = .04, d = 0.06) while the proximal mechanics and linear momentum in the ML direction did not show significant differences. A significant difference was not observed in throwing velocity between the high and low AP momentum groups (p = .27). For CMJ test, significant differences were observed in the peak vertical GRF and CI. Peak vertical GRF was 15% greater in the high AP linear momentum group with a trivial effect size compared to the low momentum group (p < .05, d = 0.17). Normalized peak GRF did not show significant differences between the two groups and the two-sample t-test revealed that body height, body mass, and lean body mass were both significantly greater in the high momentum group (Table 4-4). CI showed significant differences with a small effect size across total linear momentum in the AP direction (p = .02, d = 0.22). The high AP momentum group had 40% greater CI than the low momentum group (high momentum: 684 ± 226 kg·m·s⁻¹ vs. low momentum: 487 ± 54.4). Both absolute and normalized peak power were not significantly different between
the groups \((p = .12\) and \(p = .53\), respectively) as well as take-off velocity \((p = .43)\) and RSImod \((p = .10)\). Both groups had a non-significant stride leg dominant force output pattern (high momentum: \(0.01\pm0.04\) vs. low momentum: \(0.003 \pm 0.04, p < .70\)).

Figures 4-3, 4-4, and 4-5 show the momentum profiles of participants throughout the entire pitching cycle starting with PKH and ending with BR for linear momentum in the AP, linear momentum in the ML, and transverse angular momentum, respectively. For ML linear momentum and transverse angular momentum, the figures show the differences between the two groups, fast throwing velocity and slow throwing velocity, because they exhibited significant differences compared to each other. Integration for each momentum was calculated to get a single value that represents a participant’s total body momentum in each direction.
Table 4-1: Pitching mechanics and jump variables across throwing velocity (Fast vs. Slow).

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>p value</th>
<th>d</th>
<th>Fast</th>
<th>Slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throwing velocity (m·s⁻¹)</td>
<td>&lt;0.001*</td>
<td>0.41</td>
<td>37.7 ± 0.8</td>
<td>35.6 ± 0.5</td>
</tr>
<tr>
<td>Peak trunk angular velocity (deg·s⁻¹)</td>
<td>0.19</td>
<td>0.09</td>
<td>812 ± 93</td>
<td>877 ± 118</td>
</tr>
<tr>
<td>Peak pelvis angular velocity (deg·s⁻¹)</td>
<td>0.79</td>
<td>0.004</td>
<td>589 ± 267</td>
<td>560 ± 217</td>
</tr>
<tr>
<td>Separation time (ms)</td>
<td>0.32</td>
<td>0.05</td>
<td>26 ± 20</td>
<td>18 ± 17</td>
</tr>
<tr>
<td>Separation angle at SFC (deg)</td>
<td>0.42</td>
<td>0.03</td>
<td>36 ± 11</td>
<td>44 ± 28</td>
</tr>
<tr>
<td>AP linear momentum (kg·m·s⁻¹)</td>
<td>0.06</td>
<td>0.16</td>
<td>89 ± 15</td>
<td>82 ± 20</td>
</tr>
<tr>
<td>ML linear momentum (kg·m·s⁻¹)</td>
<td>0.01*</td>
<td>0.33</td>
<td>16 ± 5</td>
<td>7 ± 5</td>
</tr>
<tr>
<td>Transverse angular momentum (kg·m²·rad·s⁻¹)</td>
<td>0.01*</td>
<td>0.22</td>
<td>7 ± 1</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Absolute peak vertical GRF (N)</td>
<td>0.01*</td>
<td>0.22</td>
<td>2450 ± 254</td>
<td>2080 ± 352</td>
</tr>
<tr>
<td>Normalized peak vertical GRF (BW)</td>
<td>0.99</td>
<td>&lt;0.001</td>
<td>2.56 ± 0.261</td>
<td>2.56 ± 0.443</td>
</tr>
<tr>
<td>Absolute peak power (W)</td>
<td>0.15</td>
<td>0.10</td>
<td>8.06 ± 1.13</td>
<td>7.2 ± 1.41</td>
</tr>
<tr>
<td>Eccentric RFD (N·s⁻¹)</td>
<td>0.79</td>
<td>0.004</td>
<td>750 ± 428</td>
<td>796 ± 339</td>
</tr>
<tr>
<td>Concentric impulse (N·s)</td>
<td>0.54</td>
<td>0.02</td>
<td>617 ± 233</td>
<td>563 ± 134</td>
</tr>
<tr>
<td>Take off velocity (m·s⁻¹)</td>
<td>0.30</td>
<td>0.06</td>
<td>2.35 ± 0.43</td>
<td>2.56 ± 0.46</td>
</tr>
<tr>
<td>RSImod (m·s⁻¹)</td>
<td>0.37</td>
<td>0.04</td>
<td>1.1 ± 0.40</td>
<td>1.26 ± 0.39</td>
</tr>
<tr>
<td>Stride leg peak force compensation</td>
<td>0.77</td>
<td>0.01</td>
<td>0.009 ± 0.04</td>
<td>0.01 ± 0.04</td>
</tr>
</tbody>
</table>

*Significantly different (p < .05). Data are means ± SD. For each variable, a one-way factorial repeated measure ANOVA was performed with main factor throwing velocity. Variables with white background are for pitching mechanics and ones with grey background are for CMJ. BW, the abbreviation of body weight, was used as the unit for the normalized peak GRF.

Table 4-2: Height, body mass, and lean body mass across throwing velocity (Fast vs. Slow).

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>p value</th>
<th>Fast</th>
<th>Slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>0.288</td>
<td>1.88 ± 0.05</td>
<td>1.85 ± 0.06</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>0.01*</td>
<td>98.08 ± 9.07</td>
<td>83.86 ± 13.91</td>
</tr>
<tr>
<td>Lean body mass (kg)</td>
<td>0.005*</td>
<td>82.4 ± 82.0</td>
<td>71.8 ± 70.6</td>
</tr>
</tbody>
</table>

*Significantly different (p < .05). Data are means ± SD. Two sample t-test was performed to identify significant differences between fast velocity group and slow velocity group.
Table 4-3: Pitching mechanics and jump variables across total linear momentum in AP direction (High Momentum vs. Low Momentum).

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>p value</th>
<th>d</th>
<th>High M</th>
<th>Low M</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP linear momentum (kg·m·s⁻¹)</td>
<td>&lt;0.001*</td>
<td>0.39</td>
<td>105±11.4</td>
<td>76.6±10.4</td>
</tr>
<tr>
<td>Throwing velocity (m·s⁻¹)</td>
<td>0.27</td>
<td>0.06</td>
<td>37.1±1.11</td>
<td>36.5±1.38</td>
</tr>
<tr>
<td>Peak trunk angular velocity (deg·s⁻¹)</td>
<td>0.07</td>
<td>0.14</td>
<td>796±80</td>
<td>880±112</td>
</tr>
<tr>
<td>Peak pelvis angular velocity (deg·s⁻¹)</td>
<td>0.47</td>
<td>0.03</td>
<td>608±312</td>
<td>530±125</td>
</tr>
<tr>
<td>Separation time (ms)</td>
<td>0.75</td>
<td>0.006</td>
<td>24±22</td>
<td>22±14</td>
</tr>
<tr>
<td>Separation angle at SFC (deg)</td>
<td>0.36</td>
<td>0.05</td>
<td>44±29</td>
<td>35±10</td>
</tr>
<tr>
<td>ML linear momentum (kg·m·s⁻¹)</td>
<td>0.3</td>
<td>0.06</td>
<td>14±8</td>
<td>10±4</td>
</tr>
<tr>
<td>Transverse angular momentum (kg·m²·rad·s⁻¹)</td>
<td>0.04*</td>
<td>0.28</td>
<td>7±1</td>
<td>5±2</td>
</tr>
<tr>
<td>Absolute peak vertical GRF (N)</td>
<td>0.045</td>
<td>0.17</td>
<td>2420±292</td>
<td>2100±355</td>
</tr>
<tr>
<td>Normalized peak vertical GRF (BW)</td>
<td>0.35</td>
<td>0.05</td>
<td>2.47±0.317</td>
<td>2.63±0.406</td>
</tr>
<tr>
<td>Absolute peak power (W)</td>
<td>0.12</td>
<td>0.11</td>
<td>7340±1070</td>
<td>6370±1530</td>
</tr>
<tr>
<td>Normalized peak power (W·kg⁻¹)</td>
<td>0.53</td>
<td>0.02</td>
<td>7.53±1.24</td>
<td>7.92±1.46</td>
</tr>
<tr>
<td>Eccentric RFD (N·s⁻¹)</td>
<td>0.73</td>
<td>0.007</td>
<td>809±459</td>
<td>750±290</td>
</tr>
<tr>
<td>Concentric impulse (N·s)</td>
<td>0.02*</td>
<td>0.22</td>
<td>684±226</td>
<td>487±54.4</td>
</tr>
<tr>
<td>Take off velocity (m·s⁻¹)</td>
<td>0.43</td>
<td>0.03</td>
<td>2.43±0.42</td>
<td>2.57±0.42</td>
</tr>
<tr>
<td>RSImod (m·s⁻¹)</td>
<td>0.10</td>
<td>0.12</td>
<td>1.05±0.45</td>
<td>1.34±0.30</td>
</tr>
<tr>
<td>Stride leg peak force compensation</td>
<td>0.70</td>
<td>0.01</td>
<td>0.01±0.04</td>
<td>0.003±0.04</td>
</tr>
</tbody>
</table>

*Significantly different (p < .05). Data are means ± SD. For each variable, a one-way factorial repeated measure ANOVA was performed with main factor total linear momentum in anterior-posterior direction. Variables with white background are for pitching mechanics and ones with grey background are for CMJ. BW, the abbreviation of body weight, was used as the unit for the normalized peak GRF.

Table 4-4: Height, body mass, and lean body mass across AP linear momentum (High vs. Low).

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>p value</th>
<th>High M</th>
<th>Low M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>0.04*</td>
<td>1.89±0.05</td>
<td>1.84±0.56</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>0.001*</td>
<td>100.18±8.18</td>
<td>82.29±12.15</td>
</tr>
<tr>
<td>Lean body mass (kg)</td>
<td>&lt;0.001*</td>
<td>83.8±83.6</td>
<td>70.8±70.6</td>
</tr>
</tbody>
</table>

*Significantly different (p < .05). Data are means ± SD. Two sample t-test was performed to identify significant differences between high AP linear momentum group and low AP linear momentum group.
Figure 4-1: Force-time curve for fast and slow throwing velocity groups recorded in the CMJ assessment. X axis shows the entire CMJ trial starting with upright standing position (0%) and ending with take-off (100%). Y axis shows the vertical GRF.

*Significantly different ($p < .05$).
Figure 4-2: Force-time curve normalized by body weight for fast and slow throwing velocity groups recorded in the CMJ assessment. X axis shows the entire CMJ trial starting with upright standing position (0%) and ending with take-off (100%). Y axis shows the normalized vertical GRF.
Figure 4-3: Participants’ average profile of total linear momentum in the anterior-posterior (AP) direction throughout the pitching cycle. X axis shows the pitching cycle starting with peak knee height (0%) and ending with ball release (100%). Y axis shows the linear angular momentum in AP direction. Linear momentum generated along the leading axis is positive in the direction of the throw.
**Figure 4-4:** Each group’s average profile of total linear momentum in the mediolateral (ML) direction throughout the pitching cycle. X axis shows the pitching cycle starting with peak knee height (0%) and ending with ball release (100%). Y axis shows the linear momentum in ML. Linear momentum in the direction of the glove arm is positive and momentum in the direction of the throwing arm is negative. Fast throwing velocity group showed significantly greater momentum than slow throwing velocity group throughout the pitching cycle. *Significantly different ($p < .01$).
Figure 4-5: Participant’s average profile of total transverse angular momentum throughout the pitching cycle. X axis shows the pitching cycle starting with peak knee height (0%) and ending with ball release (100%). Y axis shows the transverse angular momentum. Rotation toward home plate (counter-clockwise) signifies positive angular momentum in the transverse plane. Fast throwing velocity group showed significantly greater momentum than slow throwing velocity group throughout the pitching cycle. *Significantly different ($p < .01$).
The purpose of this study was to identify the relationship between force profiles for the CMJ test and pitching mechanics with the focus on proximal segments and the lower body. Our hypotheses were partially supported by the findings of this study. The participants who threw higher velocity fastballs had significantly greater ML linear momentum and transverse angular momentum. They also showed significantly greater peak vertical GRF and power at the CMJ test and heavier body mass and lean body mass. Body mass can be considered a covariant that causes the significant difference in peak GRF and power between the fast velocity and the slow velocity groups because normalized peak GRF and power by body weight did not show significant difference between the two groups. Also, the participants who had greater linear momentum in the AP direction showed significantly greater CI at the CMJ test and they had greater body size including height, weight, and lean body mass. Overall, the results indicate that pitchers who can throw a fastball with high velocity are larger and express greater jump power that appears to translate to greater momentum toward the glove arm and angular momentum rotating toward home plate. In addition, CMJ data may be able to explain a small percentage of variability in pitching performance, typically being evaluated by throwing velocity. Previous research on momentum reported that the AP momentum has to be adequate to manage angular momentum in the transverse plane, as athletes may compensate and amplify transverse momentum to maintain throwing velocity and may increase hyper-
angulation of humerus and potential injury risks due to increased stress on the throwing arm (Ramsey et al., 2014; Ramsey & Crotin, 2016). However, it can be assumed that pitchers in this study utilized greater ML linear momentum and transverse rotational momentum to throw a higher velocity fastball, which may increase the risk of injury in faster throwing pitchers. A study investigating the relationship between the handball throwing velocity and lower body power reported the same trend as the current study that throwing velocity and lower body peak power were positively correlated with each other (Chelly et al., 2010). Although this study used the CMJ test and the study by Chelly et al. (2010) used a cycle ergometer test to measure lower body power, peak power observed during tests that do not relate to the throwing motion may be able to provide a reliable assessment regarding expected throwing performance as it relates to ball velocity.

The findings of this study also highlight the importance of lower body power for pitching performance because the CMJ is a task that mainly relies on lower body function and explosive coordination. However, significant differences were not seen in peak GRF and power between the fast velocity group and slow velocity when normalized by subjects’ body weight. The two-sample t-test revealed that body mass between the two groups were significantly different. Considering the results, body mass may play an important role in producing more power in CMJ assessment and in ML linear and transverse angular momentum which is associated with throwing a baseball at higher velocity. Other studies reported that heavier pitchers may be able to throw with higher velocity (Forsythe et al., 2016; Lehman et al., 2013). Forsythe et al. (2016) also mentioned that heavier body mass may make pitchers more prone to injury because moving heavy segments at a fast rate increase stress loaded on the throwing arm. Athletes’ power can be considered the critical
feature for throwing velocity and it may suggest that assessment for baseball pitchers in relation to pitching performance should only focus on peak power at CMJ test rather than checking the several jump kinetics parameters such as normalized peak power, E-RFD, and RSImod. Mayberry et al. (2020) reported that low E-RFD at their CMJ test was an indicator of high elbow injury risk. Pitchers with low E-RFD may have to overcompensate the slow rate of force development at the early phases of the pitching cycle, with increased force generation after the SFC phase. However, E-RFD did not impact throwing velocity in this study possibly because this “overcompensation” mechanism did not cause substantial impairment in momentum transfer for a pitch. That being said, the suggestion to use only the peak power for pitching assessment will be helpful for scientists and coaches to focus on only the necessary data that is considered meaningful for pitching performance and will lead to a reduction in the amount of data collected in CMJ assessment. Future research should examine what features observed in bilateral CMJ tests such as E-RFD and RSImod correlate with peak power. As a result, training programs can be tailored for pitchers to advance jumping-related process metrics that lead to greater peak power.

Throwing velocity did not show significant difference when participants were split into high linear momentum and low linear momentum groups. This result may indicate that more distal aspects, such as shoulder internal rotation and elbow extension velocity needs to be investigated in identifying factors that differentiate throwing velocity. Whole-body linear momentum does not seem to relate to throwing a baseball at higher velocities for Division I collegiate pitchers who participated in this study. Ramsey et al. (2014) reported that altered stride length caused significant differences in total AP linear momentum profiles while throwing velocity did not change by different stride length conditions (Crotin
& Ramsey, 2015). Pitchers having lesser linear momentum profiles may adapt their distal segment pitching mechanics to compensate the deficits in momentum. Also, greater angular momentum in the transverse plane was seen in the fast velocity group in this study, which may cause undesirable momentum transfer that leads to hyper-angulation of the throwing arm (Ramsey & Crotin, 2016). Further research is needed to examine throwing arm kinematics in association to momentum transfers in Division I college pitchers. We hypothesized that more controlled transverse angular momentum would be observed in fast velocity, as we believed higher velocity athletes would be efficient (signals of lower effort to give rise to higher velocities) and promote better momentum transfer among sequential body parts while pitching. Based on the results of this study, Division I collegiate pitchers threw the baseball with greater velocity by rotating their trunk more explosively, as the trunk occupies the greatest percentage of linear and angular momentum (Ramsey & Crotin, 2016). Strength and conditioning professionals should encourage players to gain lean body mass while working on enhancing explosive movements through plyometric training focusing on multiplanar jump and rotational power (AP, ML, and transverse plane) that incorporates equipment such as medicine balls to increase angular and linear momentum profiles. Both segment mass and velocity are critical to the calculation of momentum and may help pitchers throw higher velocity fastball when directed along the ML axis and transverse plane. However, added mass gains in the way of body fat does not contribute to contractile force and can cause decrease in acceleration of the body and increase loading on joints making movement less efficient. Explosive rotational movement has to occur within a short time frame from SFC to BR, as non-contractile mass may impact timing of momentum transfers that may impact both velocity and orthopedic health. The result of the
current study illustrates that pitchers with higher AP linear momentum had greater lean body mass than others with lower momentum. That being said, more studies evaluating differences in body composition of baseball pitchers as it relates to momentum transfer and ball velocity are warranted.

In this study, proximal pitching mechanics did not show significant differences across throwing velocity and linear momentum. van der Graaff et al. (2018) reported that pitching mechanics are likely to show significant difference when focusing on within-subject comparison instead of between-subject comparison. Their study identified significant differences in separation time with a small sample size (N = 8) by analyzing pitching data for pre-season and post-season with the within-subject design. However, significant differences were not observed when comparing data with the between-subject design, which related to our study. Much of the research that reported significant differences in pitching mechanics with between-subject analysis designs recruited pitchers from different playing levels, such as high school, college, and professional, where the current study evaluated a homogenous sample in collegiate athletes (Aguinaldo & Chambers, 2009; Aguinaldo & Escamilla, 2019; Luera et al., 2018). Thus, future research may need to analyze data within a within-subject design or have a larger number of participants to detect significance when recruiting players from a single category playing level.

The limitations of this study involved a relatively small sample size (N = 19) and a study design that was a between-subject analysis due to limited time allowed to collect data. Also, participants showed a 6% increase in average of throwing velocity when they pitched in an intra-squad game (unpublished data) compared to pitching in the laboratory
setting. There is a possibility that participants were not motivated or able to throw with their maximum effort in the lab due to pitching from a custom-made mound with force plates instead of a regulation, on-field pitching mound involving baseball cleats. One way to improve the lab setting in the future is to place turf mats on the force plates so that pitchers would be able to throw more comfortably while wearing baseball cleats. Data analysis incorporating both game and lab performance also would be effective to eliminate the issue of pitchers showing differences in throwing velocity between game and laboratory settings. Future research should focus on having participants throw with maximum effort while pitching in simulated game-like conditions involving clay mounds similar to those used during games. A proper mound could provide more frictional force interacting with players’ cleats potentially impacting ball velocities and momentum transfers seen in this laboratory study.

To practically apply the results of this study to the real-world training, strength and conditioning coaches should prescribe explosive training, such as lower body plyometric exercises involving all planes/directions with a variety of intensities and equipment such as medicine balls, hurdles, and boxes (Coleman, 2009). Olympic-style lifts may also be effective to improve a pitchers’ ability to produce lower body power, yet appropriate teaching progressions should be instituted, as the lifts are highly technical and require advanced coordination. Greater lower body strength and power translates to better pitching performance in terms of throwing velocity and linear and angular momentum profiles in the pitching cycle. Also, for pitchers throwing with greater transverse angular momentum, stabilization training for shoulder and elbow can be considered important to avoid throwing-related injuries. Increased stabilization of these joints may help pitchers to reduce
injury risk associated to increased throwing velocity and the potential of hyper-angulation of humerus. Increased body fat is not advised for pitchers, as it may cause decreased center of mass velocity that may impact momentum and also increases the potential for excessive joint stress by adding mass that does not contract.
Chapter 6

CONCLUSION

Bilateral CMJ may be effective in understanding a baseball pitcher’s capacity to throw at high velocity when peak power is calculated. Absolute lower body power is considered to have an important role in achieving elevated transverse and ML momentum that lends themselves to throwing a baseball with high velocity. It is recommended that pitchers perform lower body plyometric and rotational medicine ball training as well as gain lean body mass to enhance fastball velocity.
REFERENCES


APPENDICES

Appendix A: IRB Approval Letter

LOUISIANA TECH UNIVERSITY

MEMORANDUM

TO: Dr. David Saymanzi
FROM: Dr. Richard Keaul, Director of Intellectual Property & Commercialization
(CIPD)
ricorda@latech.edu

SUBJECT: HUMAN USE COMMITTEE REVIEW

DATE: July 30, 2019

In order to facilitate your project, an EXPEDITED REVIEW has been done for your proposed study entitled:

"Physiological and Anthropometic Characteristics of Division 1 College Baseball Players over an Entire Year"

HUC 20-066

The proposed study’s revised procedures were found to provide reasonable and adequate safeguards against possible risks involving human subjects. The information to be collected may be personal in nature or implication. Therefore, diligent care needs to be taken to protect the privacy of the participants and to assure that the data are kept confidential. Informed consent is a critical part of the research process. The subjects must be informed that their participation is voluntary. It is important that consent materials be presented in a language understandable to every participant. If you have participants in your study whose first language is not English, be sure that informed consent materials are adequately explained or translated. Since your reviewed project appears to do no damage to the participants, the Human Use Committee grants approval of the involvement of human subjects as outlined.

Projects should be renewed annually. This approval was finalized on July 30, 2019 and this project will need to receive a continuation review by the IRB if the project continues beyond July 30, 2020. ANY CHANGES to your protocol procedures, including minor changes, should be reported immediately to the IRB for approval before implementation. Projects involving NIH funds require annual education training to be documented. For more information regarding this, contact the Office of Sponsored Projects.

You are requested to maintain written records of your procedures, data collected, and subjects involved. These records will need to be available upon request during the conduct of the study and reviewed by the university for three years after the conclusion of the study. If changes occur in recruiting of subjects, informed consent process or in your research protocol, or if unanticipated problems should arise it is the Researcher responsibility to notify the Office of Sponsored Projects or IRB in writing. The project should be discontinued until modifications can be reviewed and approved.

Please be aware that you are responsible for reporting any adverse events or unanticipated problems.

A MEMBER OF THE UNIVERSITY OF LOUISIANA SYSTEM

P.O. BOX 3002 • RUSTON, LA 71272 • TEL: (318) 237-9079 • FAX: (318) 237-9079

LOUISIANA TECH UNIVERSITY
Appendix B: [HUMAN SUBJECTS CONSENT FORM]

HUMAN SUBJECTS CONSENT FORM

The following is a brief summary of the project in which you are asked to participate. Please read this information before signing the statement below. You must be of legal age or must be co-signed by parent or guardian to participate in this study.

TITLE OF PROJECT: Physiological and anthropometric characteristics of Division I college baseball players over an entire year

PURPOSE OF STUDY/PROJECT: Recently, there have been some studies which have investigated the physiological and anthropometric characteristics of basketball and rugby athletes. Studies of the physiological and anthropometric characteristics of baseball players are uncommon. To date, there has been only one study that has characterized these variables throughout an entire competitive baseball season. Therefore, the purpose of this study is to assess the physiological and anthropometric characteristics of Division I college baseball players over an entire year and to determine any relationships to offensive and defensive performance.

SUBJECTS: Because you are a Louisiana Tech men’s baseball players, you are being invited to participate in this study. If you choose to participate and give your informed consent, you will be asked to test 4 times. Testing sessions will occur in September (off-season), December (preseason), March (midseason), and May (end-season).

PROCEDURE: During the initial session (team’s first meeting), the research study will be verbally explained by the Project Director to you and you will answer a modified Physical Activity Readiness Questionnaire for Everyone (PAR-Q+) to assess your general health. If you progress through this initial PAR-Q+ screening and are approved to participate in athletics from the LaTech Medical and Athletic Training Staff, you will complete a Descriptive Data Questionnaire which will allow you to list your age and describe your baseball playing and exercising experiences.

In September (off-season), you will meet in Scotty Robertson Memorial Gym to be assessed over two weeks. Three testing stations during weeks 1 and 2 of the off-season (September) as well as 2 weeks during the preseason (December), midseason (March), and end-season (May) will occur in the Applied Physiology Lab, Memorial Gym basketball court, and Sport & Movement Science Lab. The procedures for testing will be verbally explained by the Project Director to you before testing begins in September 2019. A total testing time for players on each day will maximally take 4 hours per day; however, each player’s testing time will not take more than a maximum of 60 minutes per day. Stations representing each test will be set up around Scotty Robertson Memorial Gym. When appropriate, you will perform an active, dynamic warm-up for 15 minutes before active performance testing. Once this has been completed, you will be assigned to
one of three groups and rotate to the various stations on a given day until all are completed. During week 1 in the Applied Physiology Lab, you will have height, body mass, body composition, hydration status, grip strength, leg-low back strength measured. On the Memorial Gym basketball court, you will complete the 20-meter Pacer test, which will estimate your VO$_2$max. Against the north wall of Memorial Gym you will complete a medicine ball throw. In the Sport & Movement Science Lab, you will perform 2-leg and 1-leg vertical jump tests from force plates while using a jumping (Vertec) device. You will also perform a 2-leg standing long jump test for distance and to estimate peak power and 1-leg lateral to medial jump for distance. You will also have your vision tested by Vizual Edge computerized software.

During week 2 in the Applied Physiology Lab, you will perform three different isokinetic tests to assess your throwing and non-throwing shoulder force production on the Biodex isokinetic device. The first test will be the internal and external rotation at 90°. The second test will be an internal and external rotation at a modified 0°. The third test will be the diagonal 2 pattern flexion and extension. You will perform three different isokinetic tests to assess throwing and non-throwing lower arm force production on the Biodex isokinetic device. The first test will be the wrist flexion and extension. The second test will be forearm pronation and supination. The third test will be elbow flexion and extension. All of these tests measures force output at a specific speed (degrees per second) and range of motion. Also in the Applied Physiology Lab, you will perform a treadmill VO$_2$max test which measures the maximal amount of oxygen utilized by the body while running to failure. In the Sport & Movement Science Lab, you will pitch from a custom-made pitcher’s mound that is 60’6” from home plate. The mound will have two Bertec force plates embedded in it. Ground reaction forces, peak power, and other variables will be recorded. A 12-camera motion capture analysis system will be used to record your throwing mechanics while pitching from a custom-made pitching mound with two force plates. A Rapsodo device will be used to measure throwing velocity, spin rate, spin efficiency, pitch break, spin axis, and release point. You will wear a CosMed K5 portable metabolic unit while pitching to record oxygen consumption. Bat velocity and launch angle will be recorded with a Blast motion sensor while batted-ball exit velocity will be measured with a Pocket Radar device.

You will be re-assessed using the same tests, equipment, and procedures described above during the preseason (December), midseason (March), and end-season (May).

**BENEFITS/COMPENSATION:** At the end of this study, you will receive a Baseball Player Profile Report, which will include information about your physical fitness level and baseball performance skills. Also, you will learn how team health and skill performance data relates to offensive and defensive baseball performance. No compensation will be provided; however, you will receive a copy of the abstract upon request after the project.
RISKS, DISCOMFORTS, ALTERNATIVE TREATMENTS: You understand that Louisiana Tech is not able to offer financial compensation nor to absorb the costs of medical treatment should you be injured as a result of participating in this research. However, since you are a university athlete, you will have access to the medical and athletic training staff if an injury occurs. All tests and baseball-specific activities involved in this study present minimal risks to you, and are very similar to what you would normally experience during college baseball team practices/games. You might experience soreness. Muscle/tendon strains or soreness and ligament sprains due to near-maximal effort bat swings, pitching/throwing, and performance activities may occur. Since these protocols are typical of the daily activities during practice or games, there is little risk. Risk of injury will also be significantly reduced due to the warm-up before testing, close adult supervision, proper instruction, and a well-designed study. A very similar study to this one was conducted with the 2009 LaTech Baseball team without any injuries to the players by the same Project Director. You will be screened for health and medical risks. Specifically, you will be asked if you have had a muscle/tendon strain or ligament sprain before. If you have had an injury within the last month, you will not be able to participate. You will be considered free from injury in the lower and upper extremities if you make it through the LaTech Athletic Training/Medical Staff and PAR-Q+ health and medical screenings.

The risks associated with an exercise treadmill (VO$_2$max) test, such as fatigue, muscle soreness, irregular heartbeat, chest pain, and sudden heart attack, are about the same as those that may happen during strenuous athletic events. Severe irregular heartbeat, heart attacks, stroke, or death are extremely rare in adults with a normal, low-risk health history. To minimize these risks you will be screened by the LaTech Athletic Training and Medical Staff as well as the PAR-Q+ health and medical questionnaire. Furthermore, a trained exercise physiologist (Project Director) will perform this procedure. This test is routinely performed in the Applied Physiology Lab with Kinesiology students in exercise prescription classes without any complications. Also, you will have your heart rate and rating of perceived exertion monitored continuously throughout the test. The test will be discontinued if any abnormal heart rate or rhythm is detected. Emergency equipment (Automated External Defibrillator) in the Applied Physiology Lab and trained personnel are available to deal with unusual situations which may arise.

You understand that Louisiana Tech is not able to offer financial compensation nor to absorb the costs of medical treatment should you be injured as a result of participating in this research.

The following disclosure applies to all participants using online survey tools: This server may collect information and your IP address indirectly and automatically via “cookies.”
I,______________________________________, attest with my signature that I have read and understood the following description of the study, "Physiological and anthropometric characteristics of Division I college baseball players over an entire year", and its purposes and methods. I understand that my participation in this research is strictly voluntary and my participation or refusal to participate in this study will not affect my relationship with Louisiana Tech University, the Baseball team, or my grades in any way. Further, I understand that I may withdraw at any time or refuse to answer any questions without penalty. Upon completion of the study, I understand that the results will be freely available to me upon request. I understand that the results of the material will be confidential, accessible only to the principal investigators, myself, or a legally appointed representative. I have not been requested to waive, nor do I waive any of my rights related to participating in this study.

Signature of Participant _____________________________________ Date ___________________

CONTACT INFORMATION: The principal experimenters listed below may be reached to Answer questions about the research, subjects' rights, or related matters.

PRINCIPAL INVESTIGATORS: David J. Szymanski, dszyman@latech.edu, 318-257-4432;

CO-INVESTIGATOR: Mu Qiao, mqiao@latech.edu, 318-257-5467

Members of the Human Use Committee of Louisiana Tech University may also be contacted if a problem cannot be discussed with the experimenters:

Dr. Richard Kordial
Director, Office of Intellectual Property & Commercialization
Ph: (318) 257-2484
Email: rkordial@latech.edu