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# Effects of Pitch Repetition On Knee Joint Kinetics in Collegiate Baseball Pitchers

Shelby Anne Peel

# EFFECTS OF PITCH REPETITION ON KNEE JOINT KINETICS IN COLLEGIATE BASEBALL PITCHERS

by

Shelby A. Peel

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**ABSTRACT**

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Current baseball pitching research has focused primarily on pitcher upper extremity kinematics and kinetics. However, pitching is a full body motion where the stride leg forms a closed kinetic chain that stabilizes the pitcher as they land down the pitching mound and serves as an anchor for the pitcher to pivot around. This single-leg landing motion can occur up to 100 times per game. As such, pitchers may be susceptible to stride knee musculoskeletal injury risk. According to current statistics, 17% of pitcher injuries occur in the lower extremities. Therefore, the purpose of this study was to assess the effects of pitch repetition on 3D stride knee angles and moments in collegiate baseball pitchers. 3D stride knee angles and moments were measured during the first and last inning pitched in a simulated pitching outing. No significant change occurred in 3D stride knee angles and moments from the first inning pitched to the last inning pitched. Our findings suggest that pitch repetition may not affect 3D stride knee angles and moments, therefore may not be a primary mechanism for knee joint injury.

# PREFACE

The findings from this thesis will be submitted for publication to *Sports Biomechanics* and the formatted manuscript for this journal is presented in Chapter II. Therefore, references are formatted specifically for this journal.

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## ABBREVIATIONS

| | |
|---|---|
| BW | Body Weight |
| GRF | Ground Reaction Force |
| *d* | Cohen’s effect size |
| RPE | Rate of Perceived Exertion |

# CHAPTER I

# INTRODUCTION

## 1.1 Statement of The Problem

One of the nation's most popular sports is baseball, earning the title "America's Favorite Pastime." As many as 12,000,000 people currently participate in some level of baseball across the United States (About USA Baseball, 2016), not including the millions that play across the globe. Baseball consists of nine defensive positions, but the position that garners most attention is the pitcher. The pitcher's primary objective is to throw a baseball with speed and accuracy, with the end goal of producing outs. In order to accomplish this, a pitcher throws the baseball at velocities that are mechanically taxing to the pitching elbow and shoulder joint. Because of this overhand, high-velocity pitching movement, most pitching-related injuries occur at the elbow and shoulder joints (Bonza, Fields, Yard, & Dawn Comstock, 2009; Posner, Cameron, Wolf, Belmont, & Owens, 2011a).

As of 2010, no national database exists to document reported elbow/shoulder surgeries in all pitcher age groups (Fleisig, Weber, Hassell, & Andrews, 2009a; Posner et al., 2011a). However, the increased number of ulnar collateral ligament injuries treated at an orthopedic center from 1994 to 2010 supports the idea that elbow injuries are on the rise. In 1994, the Andrews Sports Medicine and Orthopaedic Center reported six youth pitchers who required ulnar collateral ligament reconstruction (i.e. Tommy John's surgery) (Fleisig et al., 2009a). Almost 16 years later, that same center reported 1,607 cases of ulnar collateral ligament reconstruction surgery in youth pitchers. Major League

Baseball has also seen increased injury rates in pitchers. From 1989 to 1999, the number of pitchers placed on the disabled list increased from 118 pitchers to 182. This indicated that an average of 48.4% of all Major League Baseball players reported to the disabled list during this period (Conte, Requa, & Garrick, 2001). However, the study failed to state the type of injuries suffered by the pitchers (Conte et al., 2001). Understandably, most current research literature focuses on upper extremity injuries and preventative measures (Fleisig et al., 2009a).

While it is imperative to understand the mechanics of the upper extremities for preventing injuries, pitching is a full-body motion that requires much lower extremity action. What separates baseball from other throwing sports is that no other sport consists of this repetitive, single-leg, downhill landing. The landing leg is called the stride leg. Pitching incorporates a kinetic chain to generate energy from the lower extremities and transfer it to the upper extremities to produce ball velocity (Fleisig, Barrentine, Escamilla, & Andrews, 1996). One particular joint that requires more attention is the stride knee.

The stride knee is responsible for eccentric control of the vertical displacement of the pitcher's center of mass immediately following the stride step down the mound. The stride knee experiences the same repetitive downhill landing motion up to 30 times an inning, and 100 times a game (Campbell, Stodden, & Nixon, 2010) with the repetitive knee motion throughout a game, it is logical that overuse injuries could occur. In 2011, Posner et al. examined injury rates of Major League Baseball players between the 2002-2008 regular season (Posner et al., 2011a). It was reported that 16.9% of injuries occurring in pitchers were to the lower extremities. Per season, the region that experienced the most injuries were the knee/hamstring (7%), followed by the hip/groin region (5.7%), and the foot/ankle region (2.9%) (Posner et al., 2011a). This repetitive lower extremity movement may partly explain why pitchers experience a variety of other musculoskeletal injuries

It has been suggested that the stride knee is susceptible to connective tissue damage (Guido & Werner, 2012). A prime example of this would be New York Yankees starting pitcher C.C. Sabathia. According to ESPN, Sabathia missed most of the 2014 Major League Baseball season due to discomfort in his stride knee caused by a bone spur, ultimate leading to surgery. Magnetic resonance imaging of Sabathia's stride knee showed degeneration of the knee, with almost no cartilage left under his patella. While Sabathia is one of the few pitchers to have received surgery on his stride knee, the number of unreported stride knee injuries and symptoms is unclear. Ultimately, this type of cartilage degeneration has the potential to lead to knee long-term knee damage, such as osteoarthritis. In 2010, Meir et al. conducted a retrospective analysis of injuries and complications reported by retired Australian baseball players (Meir, Weatherby, & Rolfe, 2010). Out of the 75 retired players surveyed, knee osteoarthritis was the most common degenerative injury (Meir et al., 2010). However, the authors failed to report the position of each player who developed knee osteoarthritis (Meir et al., 2010).

Although it is difficult to make a connection between specific modifiable stride knee mechanics and long-term repercussions such as knee osteoarthritis development, there are unavoidable factors that can be detrimental to the stride knee. One such factor is repetition. Considering that body control during pitching single-leg landings originates from the bottom of the kinetic chain, there is a lack of research focused on the effects of repetitive lower extremity motion and specifically, motion of the knee joint. There is a small amount of data on stride knee joint motion, ground reaction forces (GRF) acting below the stride leg, and activation levels of the muscles involved with controlling the stride knee. Unfortunately, to date, there is even less research on stride knee mechanics as pitch count increases.

Although there are a few studies that investigate how repetition affects lower extremity motion (Escamilla et al., 2007; Grantham, Byram, Meadows, & Ahmad, 2014; Murray, Cook, Werner, Schlegel, & Hawkins, 2001), essential information to better understand stride knee mechanics is still missing. It is possible that repetition can lead to faulty mechanics, which in turn could potentially lead to musculoskeletal injury. A more in depth understanding of the mechanics of lower extremity joints such as the knee, researchers, clinicians, and coaches may be able to optimize career longevity by preventing debilitating pitching injuries.

## 1.2 Literature Review

The first purpose of this literature review is to summarize and discuss current literature findings of stride knee mechanics of the stride leg during pitching. The second purpose is to summarize current scientific findings regarding how pitch repetition (i.e., increased pitch count) may alter knee joint mechanics.

### *The Phases of Pitching*

Before discussing specific movements of the knee joint during the stance phase of the stride leg, it is important to introduce the phases of the baseball pitch. Pitching is a cycle, most commonly broken down into six phases: wind-up, stride, arm cocking, arm acceleration, arm deceleration, follow-through (Fleisig et al., 1996) (Figure 1). It is important to understand what each of these six phases mean and how the stride knee plays a role in each phase.

**Pitching Cycle Phases**

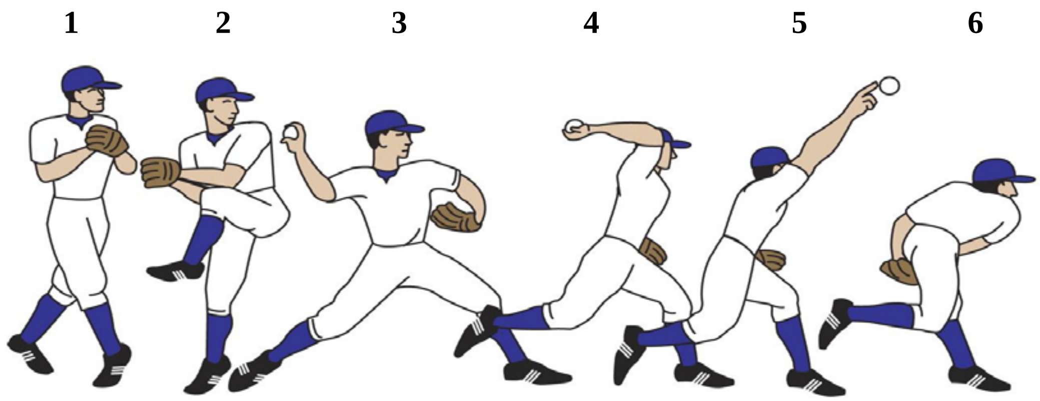


**Figure 1**.The 6 phases of the pitching cycle starting with 1.) wind-up, 2.) stride phase, 3.) arm-cocking phase, 4.) arm acceleration phase, 5.) arm deceleration phase, 6.) follow-through.

The first phase in the cycle is the wind-up. Wind-up begins with the pitcher's first movement of lifting the stride leg off the pitching rubber, and ends with the stride leg lifted to its maximal height off the mound (Fleisig et al., 1996). The next phase, stride phase, occurs when the pitcher starts to move the stride leg toward the catcher from this maximal height (Fleisig et al., 1996). Stride phase ends when the pitcher has fully extended toward the catcher, and the stride foot has made contact down the pitching mound (Fleisig et al., 1996). While the stride phase is nearing completion, the arm-cocking phase starts. This phase starts with initial stride foot contact with the mound and ending at maximal shoulder external rotation (Fleisig et al., 1996). During this phase, the stride knee flexes to absorb the impact of landing on the mound. Succeeding this phase is arm acceleration phase. This phase is considered the most dynamic portion of the cycle, starting from maximum shoulder external rotation, and ending at the instance of ball release (Fleisig et al., 1996). The main role of the stride knee here is to help maintain stability for the pitcher's body as it moves from a bilateral stance to a unilateral stance (Fleisig et al., 1996). The arm deceleration phase starts at ball release to maximum internal rotation of the shoulder. The last phase, follow-through, starts at maximum shoulder internal rotation and continues to the completion of the pitch (Fleisig et al., 1996). The stride knee continues to play a role in stability for the body, but has a reduced role compared to that seen in previous phases. The stride knee plays its biggest role in terms of absorbing impact and providing stability during the stride foot contact, maximum shoulder external rotation, and ball release phases. While it is imperative to understand the stride knee's role in the pitching cycle, it is also important to understand how other factors affect mechanics of the stride knee.

### *Stride Leg Mechanics during Pitching*

Beginning with pushing off the rubber plate on the mound in the wind up phase, lower extremities create a closed-kinetic chain (Tippett, 1986a) that serves as the main force generator used during pitching (Stodden, Langendorfer, Fleisig, & Andrews, 2006). The resultant GRF is transferred proximally to the upper extremities, so the pitcher can increase ball velocity (MacWilliams, Choi, Perezous, Chao, & McFarland, 1998; Stodden et al., 2006). Joint injury or poor mechanics will produce unwanted stress at different joints along the closed-kinetic chain (MacWilliams et al., 1998). As discussed previously, the knee joint stabilizes the body when the pitcher moves from two-leg to single-leg stance during the pitching cycle. During this landing portion of the pitching cycle, the pitcher must pivot around the weight-bearing stride leg to counteract the pitcher’s upper body angular momentum (Figure 2).

**Figure 2**. Examples of stride leg position and upper/lower extremity counter angular momenta immediately following landing during a baseball pitch

The hip joint plays an important role for proper orientation and stabilization of the pelvis (Dillman, Fleisig, & Andrews, 1993; Laudner, Moore, Sipes, & Meister, 2010; Tippett, 1986a). With proper pitching mechanics, the stride foot lands almost directly in line with the back trail foot with toes pointed slightly inward (Dillman et al., 1993). However, variation in stride foot placement can affect stride hip rotation. For example, if the foot is placed too medially, the pitcher’s stride hip cannot externally rotate properly. This lack of rotation prevents optimal energy transfer from the lower extremities (Dillman et al., 1993). If the foot is placed too laterally, the hips will rotate too soon, causing premature energy transfer from the lower extremity and improper trunk rotation (Dillman et al., 1993). Optimal strike foot placement in achieved with stride leg hip external rotation before the foot strikes the ground (Tippett, 1986a). With this closed-kinetic chain movement, proximal energy transfer starts with GRF development during trail-leg push-off and GRF absorption during stride leg stance phase.

### *Ground Reaction Forces*

It is not only important to understand stride knee mechanics, but we must also consider the forces that initiate the closed-kinetic chain during a pitching cycle. Baseball is the only throwing sport that requires the athlete to throw from an elevated surface (i.e. downhill landing) (Guido & Werner, 2012). From the downhill landing, pitchers experience large resultant GRF under the stride foot (Guido & Werner, 2012). One study found that during stride leg stance, peak anterior-posterior shear GRF reached 0.72 body weight (BW), peak medial-lateral shear GRF reached 0.1 BW, and peak vertical GRF reached 1.5 BW (MacWilliams et al., 1998). Guido et al. found that pitchers experienced peak vertical GRF of over 2 BW and that peak medial-lateral GRF reached 0.45 BW (Guido & Werner, 2012). The authors did not report pitch velocity and thus, differences in pitch velocity could explain the discrepancies in GRF findings. Since the effects of GRF are compounded with the downhill landing to affect lower limb joint mechanics in pitching, coaches and trainers should also consider paradigms of injury prevention of lower extremity joints.

### *Knee Joint Biomechanics*

During pitching, the stride knee flexes as the pitcher lunges forward with the stride leg, before foot contact with the ground (Dillman et al., 1993). Once initial foot contact is made, stride knee flexion continues while weight bearing (i.e. eccentric knee extensor contractions) (Campbell et al., 2010) to absorb the impact (Werner, Suri, Guido Jr, Meister, & Jones, 2008) and then extends once the pitcher’s center of mass moves forward over the stride leg (Dillman et al., 1993). Mean stride knee flexion of 46.8±8.5°

has been observed at stride foot contact, moving to 38.0±13.7° at ball release (Kageyama, Sugiyama, Kanehisa, & Maeda, 2015). Campbell et al. reported that knee extensors, as well as ankle plantarflexors, serve as primary knee stabilizers to help decelerate the upper body during the stance phase after the ball has been released (Campbell et al., 2010). Between stride foot contact and ball release the gastrocnemius, vastus medialis, and rectus femoris all surpassed 100% of their maximum voluntary isometric contraction levels (Campbell et al., 2010). From ball release to 0.5 seconds after ball release, the gastrocnemius had activity levels of over 100% of their maximum voluntary isometric contraction levels while the activation of vastus medialis and rectus femoris was reduced to 89 and 47%, respectively (Campbell et al., 2010). Although sagittal plane knee kinematics are well understood, frontal and transverse plane strike knee motion during pitching is not. Further, current research has investigated knee joint kinetics (e.g. moments, angular power and work) during pitching is scarce. The mean stride knee extension moment is -0.1±0.2 Nm/kg at stride foot contact and -1.0±0.9 Nm/kg at ball release during pitching (Kageyama et al., 2015). Joint kinetic variables provide important information regarding resulting forces acting on the knee joint. In fact, knee moments often act as surrogate measures of joint loading (Mündermann, Dyrby, Hurwitz, Sharma, & Andriacchi, 2004; Prodromos, Andriacchi, & Galante, 1985; Schipplein & Andriacchi, 1991; Sharma et al., 1998). Since knee biomechanics are influenced by ankle and hip motion (Bartlett, Wheat, & Robins, 2007; Pohl, Messenger, & Buckley, 2006), it is important to consider ankle and hip motion during pitching to fully understand knee mechanics.

### *Ankle and Hip Joint Biomechanics*

Although the exact implications of ankle and hip joint movements on knee mechanics during pitching have not received much attention in the literature, as previously discussed, proper internal rotation of the stride hip is needed to properly transfer energy to the upper extremities (Dillman et al., 1993). Previous research has shown that collegiate pitchers experience mean hip internal rotation of -48.5±8.6° at stride foot contact and -16.1±8.8° at ball release (Kageyama et al., 2015). If this rotation is disturbed, energy transfer to the upper extremities is also disrupted.

With respect to the frontal plane, Kageyama et al. reported mean hip abduction at stride foot contact of -38.1±6° in collegiate pitchers (Kageyama et al., 2015). As the pitcher moved from stride foot contact to ball release, the stride hip entered hip adduction with mean values of 37.1±14.0° (Kageyama et al., 2015). Hip adductor muscle activation two seconds immediately after stride foot contact is 84±12% of maximal isometric contraction using manual muscle test (Yamanouchi, 1998). Yamanouchi reported that the hip adductors were the only leg muscle tested to surpass 80% of their maximal isometric contraction (Yamanouchi, 1998). This finding is not surprising since as the stride foot lands, the adductors contract to pull the body forward rapidly (hip adduction) to increase forward velocity. The author also indicated that hip adductors were the main muscles involved in trunk and pelvis stabilization and serve as the braking muscles for decelerating the upper body in the later stages of the pitching cycle (Yamanouchi, 1998).

Further, injuries to the hip joint or hip muscles (e.g. labrum tear, strains, and fatigue) may alter transverse plane hip kinematics (Powers, 2010). Although this work was not directly focused on the effects of hip motion on knee mechanics, changes in transverse plane hip rotations are expected to alter knee joint mechanics, which could consequently alter connective tissue stresses (Powers, 2010). Specifically, increased contralateral pelvic drop adducts the stance limb hip during single-leg stance, which increases compressive forces in the medial compartment of the knee (Powers, 2010).

Additionally, increased ankle eversion (i.e. frontal) during single-leg stance increases tibial internal rotation (Pohl et al., 2006), which in turn increases internal rotation of the knee joint. Greater peak internal rotation has been associated with retrospective running injuries specific to the knee and hip joints (Ferber, Noehren, Hamill, & Davis, 2010; Noehren, Davis, & Hamill, 2007; Willson & Davis, 2008). Although baseball pitching and running are different sporting activities, the fundamental lower limb motion of single-leg stance is quite similar. Therefore, repetitive stride limb stepping with altered ankle motion over time could be responsible for proximal joint injuries in pitchers.

Since changes in ankle and hip movements have potential negative effects on knee joint mechanics, it is imperative to understand their specific biomechanics during pitching to better understand injury mechanisms. In addition to understanding secondary joint effects on knee mechanics, the repetitive action of pitching must also be considered to fully understand injury mechanisms.

### *How May Pitch Repetition Affect Joint Mechanics?*

Movement repetition is an unavoidable factor for most athletes. Even though pitchers are given a three- or five-day rest period in between pitching outings, pitch repetition still plays a role in pitching mechanics breakdown during a game. When studying movement repetition, much of the current research focuses in the upper extremities (Gandhi, ElAttrache, Kaufman, & Hurd, 2012). Coaches, trainers, doctors, and players are concerned with limiting the number of pitches to avoid extreme shoulder and arm muscular fatigue. However, researchers and clinicians have seldom considered the effects of increased pitch count on lower extremity mechanics. With a higher pitch count and likelihood of increased muscular fatigue, probability of musculoskeletal injury development could be greater (M. J. Mullaney, McHugh, Donofrio, & Nicholas, 2005; Murray et al., 2001). Fatigued muscles cannot produce as much force as fully rested muscles (Mair, Seaber, Glisson, & Garrett, 1996). Weakened lower extremity muscles may have a sub-optimal ability to eccentrically control knee and hip joint movements to absorb forces transferred from the ground (Mair et al., 1996). As a result, links within the closed-kinetic chain may be altered (Burkhart, Morgan, & Kibler, 2003). Changes within the kinetic chain could alter the force absorption function of each joint to yield injurious stresses on bones, articulations, and connective tissue (Escamilla et al., 2007). Since pitching requires a controlled downhill single-leg landing, observing knee mechanics in single-leg movements in fatigued states can help understand how muscular fatigue could compromise joint mechanics during pitching (Campbell et al., 2010).

Fatiguing exercise of the knee extensors, hip extensors, plantarflexors and dorsiflexors (two sets of 50 step-ups using the dominant leg with one minute of rest between sets) changes mechanics during single-leg 30 cm drop landings in healthy adult men (Orishimo & Kremenic, 2006). In particular, increased knee flexion and reduced peak knee extension moment and negative work were observed. The authors suggest that increased eccentric knee extensor demand was necessary to maintain whole body stability. These findings suggest that knee mechanics could also be altered due to muscular fatigue following a higher number of pitches. These data may be important to understand the implications of pitch repetition for lower extremity injury risks.

Guido et al. suggested that the increased shear GRF caused by the forward downhill lunging and rotational components of pitching may be transferred to the knee joint (Guido & Werner, 2012). The knee then could be susceptible to connective tissue damage, especially if increased pitch count results in muscular fatigue (Guido & Werner, 2012). Even though it is rare for a pitcher to suffer a traumatic knee injury, it is logical that the repetitive motion of downhill throwing could cause overuse injuries to the knee joint and surrounding connective tissue. Unfortunately, since the damage caused by repetitive loading of the knee may not produce immediate symptoms, it may be difficult for pitchers to sense and prevent the damage from occurring over time. As previously mentioned, little research has been conducted on the effects of pitch repetition on lower extremity joint biomechanics, specifically the stride knee.

Only four studies investigated the impact of pitch repetition on several biomechanical variables within the upper and lower extremities. Three of the four studies concluded that fatigue has a significant impact on stride knee mechanics during landing (Grantham et al., 2014; Murray et al., 2001; Pei-Hsi Chou et al., 2015). Knee flexion was significantly increased from the first to the last pitches collected in all three studies. While two of the studies eluded to this inference (Grantham et al., 2014; Murray et al., 2001), only one concluded that increased knee flexion toward the end of a lab-simulated pitching outing indicated overall muscle fatigue and tiredness (Pei-Hsi Chou et al., 2015).

Murray et al. reported that during the first inning of a baseball game, pitchers had an average peak stride knee flexion of 40° at ball release (Murray et al., 2001). However, by the last inning, knee flexion had increased to 48°. The increased stride knee flexion was observed in parallel with a reduction in average ball velocity from first to last inning (i.e. 90 mph to 85 mph) (Murray et al., 2001). Investigators stated that this finding might be suggestive of a relationship between pitch repetition and a reduction in peak knee flexion (Murray et al., 2001). While this study found significant differences in peak knee flexion with increased pitch count, they only analyzed one pitch per inning from the first to the last inning ( Murray et al., 2001).

Grantham et al. followed this approach and continued live game analyses. The investigators observed several time points during a single game and throughout a season (Grantham et al., 2014). Eleven collegiate pitchers were filmed during games throughout a season (Grantham et al., 2014). The first, 15$^{th}$, and 30$^{th}$ fastball pitches (when available), of each inning were recorded and analyzed for 26 kinematic variables (Grantham et al., 2014). By following a pitcher throughout 26 games of the season for 162 innings (Grantham et al., 2014), investigators were able to examine how fast pitch repetition affected pitchers within the progression of a single game as well as the duration of a season (Grantham et al., 2014). Since they found that stride knee flexion was increased throughout the progression of a season, even after having rest days, their findings suggest that coaches and pitchers should seek optimal training methods with the specific aim of reducing or preventing these repetition-related changes. It is important to note that these studies were conducted during live games, which increases the external validity of the findings. However, the degree of internal validity and reliability of knee flexion measurements may be low.

One downfall in conducting pitch repetition studies in a laboratory setting is that pitchers, even after a high pitch count, may not experience similar levels of muscular fatigue as they would in actual games (Escamilla et al., 2007). In fact, Escamilla et al. (2007) found that collegiate pitchers showed consistent upper and lower extremity mechanics after throwing more than 100 pitches. They reported that stride knee flexion at stride knee contact was unchanged from first inning to last inning pitched (47±11° and 47±12°, respectively) while stride knee flexion at ball release from first inning to last inning pitch was 41±13° and 39±16°, respectively. Pitchers tested in a lab environment may not perform or push themselves as hard as they would in an actual game situation since their level of extrinsic motivation may be lower. However, Pei-His Chou et al. (2015) did find a significant increase in peak stride knee flexion after a simulated pitching outing in a laboratory setting. Although their pitchers also threw 100 pitches, they tested a younger population of high school pitchers (i.e. 16.77 ± 0.73 years) (Pei-Hsi Chou et al., 2015).  More research is needed to know the effects of pitch repetition on lower extremities mechanics.

However, researchers have to be careful that their in-lab pitching protocols can actually achieve a level of muscular fatigue and motivation similar to game situations. Knowledge of results (e.g. ball speed radar) and other cues may be useful to motivate the pitchers during laboratory throwing protocols (Crotin, Kozlowski, Horvath, & Ramsey, 2014). While research reports increased stride knee flexion, it is also important to understand potential changes in frontal and transverse plane mechanics. In other single-leg high impact movements such as running, frontal and transverse plane lower extremity mechanics have often been related to overuse injuries (Dierks, Manal, Hamill, & Davis, 2008; Eskofier, Kraus, Worobets, Stefanyshyn, & Nigg, 2012; Messier & Pittala, 1988; Noehren et al., 2007; Noehren, Sanchez, Cunningham, & McKeon, 2012; Noehren, Schmitz, Hempel, Westlake, & Black, 2014; Pohl, Mullineaux, Milner, Hamill, & Davis, 2008; Stefanyshyn, Stergiou, Lun, Meeuwisse, & Worobets, 2006).

### *Other Factors*

While pitch repetition may alter lower extremity mechanics, other factors should be mentioned. Current research has shown that age and skill level of pitchers appears to affect stride knee kinematics. Adolescent pitchers (age range 10.5-14.7 years) show stride knee flexion at foot contact of 49±12° and 41±16° at ball release (Milewski, Õunpuu, Solomito, Westwell, & Nissen, 2012). Younger (19.7±0.5 years) and older (29.5±2.0 years) professional pitchers, however, use 38.5±11.4° and 27.8±12.5° and, 43.8±7.4° and 39.9±13.7° of knee flexion at stride foot contact and ball release, respectively (Dun, Fleisig, Loftice, Kingsley, & Andrews, 2007). Due to limited data, Mileweke et al. (2012) suggest it is difficult to conclude with confidence that there is increasing or decreasing peak stride knee flexion as pitchers age.

Pitch type and velocity also appear to affect stride knee mechanics. Pitch velocity may be the most influential factor to explain differences in peak knee flexion among different pitch types (i.e. fastball, curveball, change-up, and slider). Escamilla et al. studied peak knee flexion during the four most common pitch types in 16 collegiate pitchers (Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998). They found that knee flexion was the largest during the change-up compared to the other three pitches. This finding was confirmed in a separate investigation studying 20 collegiate pitchers where peak knee flexion was largest during the change-up compared to pitches previously mentioned (Fleisig et al., 2006). The slower pitch velocity in curveballs and change-ups appears to be the primary explanatory factor for increased stride knee flexion. Variations in stride length could also affect stride knee mechanics. While altered stride length in pitching is not well-documented, increased stride length during running has been associated with increased hip and knee extension moments, increased GRF, and increased energy absorption at the knee joint (Derrick, Hamill, & Caldwell, 1998; Seay, Selbie, & Hamill, 2008; Stergiou, Bates, & Kurz, 2003). Therefore, changes in stride length during pitching would also be expected to alter lower limb joint kinetics. Since lower extremity kinematics appear to be affected by age, skill, pitch type, and pitch speed, it is important for scientists to consider these factors when assessing lower extremity mechanics during pitching.

### 1.3 Literature Gaps and Limitations

Research has primarily focused on the mechanics of the upper extremities and causes of injury within the shoulder and elbow during pitching. While there is some data on lower extremity mechanics during pitching, this area of research still warrants further investigation. Pitch repetition may alter stride knee mechanics, which could consequently disrupt the kinetic chain to alter pitching performance and potentially produce injurious joint stresses. If coaches and trainers can better understand the effects of pitch repetition on lower extremity joint mechanics, they may be able to more optimally train and prepare their pitchers to prevent injury risks.

### 1.4 Research Questions and Hypotheses

Based on current literature findings and limitations, the following research question and hypothesis were formulated:

**Research Question:** What are the effects of game-simulated pitch count on peak sagittal, frontal, and transverse plane stride knee angles and moments in collegiate pitchers?

> ***Hypothesis:*** As pitch count increases, magnitude of peak knee joint angles and moments would increase.

# CHAPTER II

## The Effects of Pitch Repetition on Stride Knee Kinetics in Collegiate Baseball Pitchers

**Shelby A. Peel, Max R. Paquette, Brian K. Schilling, Lawrence W. Weiss**

*Manuscript in preparation for Sports Biomechanics*

### Introduction

Baseball is a vastly popular sport across the globe, with professional leagues in North America, South America, Europe, Asia, and Australia. In America alone, as many as 12 million people currently participate in organised baseball (About USA Baseball, 2016). Even though there are nine positions for players to fill, the pitcher garners the most attention. An individual pitcher may go through the pitching motion up to 100 times per game. Accumulated fatigue from the repetitive pitching action may yield poor upper and lower limb mechanics, which in turn could cause musculoskeletal injury (Murray et al., 2001). To minimise the effects of upper extremity muscular fatigue, coaches typically count pitches in order to limit the number thrown by an individual during a game (Lyman, Fleisig, Andrews, & Osinski, 2002).

As pitchers run a high risk of upper extremity injuries (Conte et al., 2001; Conte et al., 2015; Fleisig, Weber, Hassell, & Andrews, 2009b; Fleisig et al., 2015; Posner, Cameron, Wolf, Belmont, & Owens, 2011b), the vast majority of research on baseball pitching has focused on upper extremity joints (Escamilla et al., 2007; Fleisig et al., 2015; Grantham et al., 2014; Murray et al., 2001). Although upper extremity injuries are more common, approximately 17% of injuries in pitchers occur in the lower extremities

(Posner et al., 2011b). Per season, 2.9% of injuries occur at the foot/ankle, 7% at the knee/hamstring, and 5.7% at the hip/groin region (Posner et al., 2011b).

Pitching incorporates closed kinetic chain events, generating energy from the lower extremities that is transferred to the upper extremities (Fleisig et al., 1996; Tippett, 1986b). The pitcher must push off the elevated mound with the trail leg, land with the stride leg in a lunge position, and pivot around the weight-bearing stride leg to counteract the angular momentum of the upper body. During the landing phase, the knee extensors eccentrically control knee flexion (Campbell et al., 2010). The repetition of these single-leg landing mechanics during a baseball game provides likely mechanisms for lower extremity musculoskeletal injury risk. Although a few studies have investigated lower extremity mechanics during pitching, additional evidence is warranted to further understand injury mechanisms including the effects of pitch count on lower extremity biomechanics.

Research shows that as pitch count increases, stride knee peak flexion increases (Grantham et al., 2014; Murray et al., 2001; Pei-Hsi Chou et al., 2015). Murray et al. (2001) reported pitchers having an average peak stride knee flexion of 40° in the first inning, while flexion increased to 48° in the last inning ($6^{th}$ inning) during a live game. A different laboratory-based study found a small increase in peak flexion of the stride knee (pre=53.6 $\pm$ 21.5 deg; post=56.1 $\pm$ 22.2 deg, $d$=0.12) in high school pitchers after a 100-pitch simulated game (Pei-Hsi Chou et al., 2015). This effect size ($d$) is interpreted as small. Since the knee extensors play an important role in controlling knee flexion during the single-leg lunge action of pitching (Campbell et al., 2010), the increased knee flexion corresponding to a higher pitch count number may be the result of muscular fatigue of the knee extensors. Others have reported no changes in knee flexion from beginning to end of a simulated pitching outing in a laboratory setting (Escamilla et al., 2007). Discrepancies in previous findings may be due to differences in pitch velocity, testing setting (e.g. in-lab vs live game), pitcher age, and the degree of muscular fatigue.

Although sagittal plane knee kinematics have been studied, other lower extremity joint kinematic and kinetic variables have not received much attention in the literature. Joint moments often act as surrogate measures of joint loading (Mündermann et al., 2004; Prodromos et al., 1985; Schipplein & Andriacchi, 1991; Sharma et al., 1998). Further, knee biomechanics are influenced by ankle and hip kinematics (Bartlett et al., 2007; Pohl et al., 2006). Thus, it would be worthwhile to understand the effects of pitch repetition on lower extremity joint moments and kinematics to expand our current understanding of injury mechanisms during pitching.

The aim of this study is to assess the effects of game-simulated pitch repetition on three-dimensional (3D) stride knee angles and moments in collegiate baseball pitchers. We hypothesised that peak knee joint angles and moments would increase concomitantly with pitch count. This work also aims to assess the effects of pitch repetition on ankle and hip biomechanics to further understand secondary mechanisms. By doing so, researchers, clinicians, and coaches may be able to optimise career longevity by preventing lower extremity pitching injuries.

## Methods

*Participants*

A convenience sample of eight NCAA Division 1 collegiate baseball pitchers (20.3 ± 1.8years; 92.0 ± 12.5kg; 1.88 ± 0.06m) volunteered for the study. All pitchers were currently uninjured and had started their offseason long pitching practices in preparation for spring season. Four pitchers had a history of injury (three with upper extremity injuries, one with a lower extremity injury). However, all pitchers were fully recovered and cleared by a physician to participate in maximal effort activities, and team head coaches were aware of their participation in this investigation. Prior to testing, pitchers were informed of all testing procedures and provided written informed consent approved by the Institutional Review Board.

*Procedures*

Pitchers reported to the laboratory for one testing session, similar to previous research (Escamilla et al., 2007). Once height and body mass were measured, pitchers were given unlimited time to complete their pre-game warm up routine and practice with the indoor pitching mound (6" stride off game mound, Portolite Products, Inc. Delano, MN). This practice was used to ensure that the stride foot of all pitchers landed on the force platform on the laboratory floor. An 8-camera 3D motion capture system (240 Hz, Qualisys AB, Göteborg, Sweden) and a force platform (1200 Hz, AMTI, Inc.) were used to obtain 3D kinematic and ground reaction force (GRF) data, respectively. Following the warm-up, 10 anatomical reflective markers were placed over the right medial and lateral femoral epicondyles, medial and lateral malleoli, and first and fifth metatarsal heads. These markers were used to define the thigh, shank and foot segments, respectively.

Markers were also placed over the right and left iliac crests and greater trochanters of the femurs to define the pelvis segment. Clusters of four non-collinear markers on semi-rigid thermoplastic shells were attached to the posterior pelvis, lateral thigh and shank using neoprene wraps to track these segments during testing trials. Three non-collinear markers on a semi-rigid thermoplastic shell were secured directly on the posterior surface of the heel for the stride foot shoe. A marker was also placed on the posterior surface on the left heel on the trail foot shoe. A one-second static calibration trial was recorded and the 10 anatomical markers were removed before the start of the pitching protocol.

*Pitching Protocol*

For the pitching protocol, two pitchers were tested during the same testing session. Pitchers alternated every half inning to simulate the pitching rotation during a real game[9]. Pitchers completed as many simulated innings as possible, but were limited to a maximum of 6 innings to minimise injury risk and as per the instructions of their coach. Pitchers were instructed to pitch 15 maximal effort pitches during each inning (Escamilla et al., 2007).  A target was positioned in a netted cage 10 meters from the front edge of the pitching rubber, and was placed 1.14 meters off the ground. This was equivalent to the ball landing 0.91 meters above home plate (within the strike zone) since we could not accommodate the standard 18.4 meters mound-to-home plate distance in the laboratory.

Five warm-up pitches were allowed before the start of each inning (Crotin et al., 2014). Once handed a baseball, the pitcher had a maximum of 20 seconds to deliver the pitch in accordance with current collegiate baseball rules (Paronto, 2014). When the pitcher completed their 15 pitches, they were given nine minutes of rest until the start of their next inning (Crotin et al., 2014). Pitchers were instructed to pitch a variety of pitches during their inning (e.g. fastball, curveball, change-up, and slider) as per their coach's instructions. However, they were asked to pitch *only fastballs* during data collection time points as research has shown different pitch types can affect knee mechanics (Fleisig et al., 2006).

Data were collected at two different time points: 1) the first five pitches during inning one and, 2) the last five pitches during the last inning pitched. A radar gun (Ball Coach, Pocket Radar, Santa Rosa, California) was used to record pitch speed to help quantify potential effects of fatigue (i.e., reducing pitch speed) and to provide pitch speed feedback to pitchers. If the pitchers felt that they had reached fatigue and could no longer pitch with proper mechanics before six innings were completed, the testing session was terminated. Pitchers were also asked to rank their level of perceived lower extremity exertion using the Borg's rate of perceived exertion scale (6-20) (Pei-Hsi Chou et al., 2015) after each data collection period.

*Data Processing & Analyses*

Visual3D (C-Motion, Germantown, MD) was used to compute 3D joint kinematic and kinetic variables. A threshold of 20 N of the vertical GRF was used to detect the start of the stride leg loading phase. Maximal stride knee extension after foot contact was used to detect the end of the stride leg loading phase. A right-hand rule with a Cardan rotational sequence (x-y-z) was used for the 3D angular computations where x represents the medial-lateral axis, y represents the anterior-posterior axis, and z represents the longitudinal axis. Kinematic data were interpolated using a third-order least-squares fit to three data points with a maximum gap of 10 frames. Kinematic and GRF data were then both filtered using a Butterworth second-order dual-pass filter with a cutoff frequency of

8 Hz (Kristianslund, Krosshaug, & van den Bogert, Antonie J, 2012). This cutoff frequency was found by performing a Fast Fourier transform on unprocessed pilot GRF data prior to study data collection.

Joint angular kinetic variables were computed using inverse dynamics, and net internal moments were normalised to body mass ($Nm \cdot kg^{-1}$). Four dependent knee joint kinematic variables were measured: peak knee flexion, peak knee abduction, peak knee adduction and, peak knee internal rotation angles. Peak knee flexion, peak knee adduction, and peak knee internal rotation angles occur during the first 50% of the loading phase. Peak knee abduction angle occurs during the last 50% of the loading phase. Four dependent knee joint moment variables were measured: peak knee flexor, peak knee extensor, peak knee abduction and, peak knee internal rotation moments. Peak knee extensor moment occurs during the first 50% of loading phase while peak knee flexor moment occurs during the last 50% of loading phase. Peak knee abduction and internal rotation moment occur directly at 50% of the loading phase. For all variables, the averages of the five fastball pitches at the beginning of the first inning and during the last inning pitched were included in the statistical analyses.

*Statistical Analysis*

A within-subject repeated measures ANOVA was used to compare the mean of all 11 dependent variables at the start and end of the pitching protocol with least significant difference pairwise mean comparisons.  Data normality was assessed using the Shapiro-Wilk test. The alpha level was set to $p \leq 0.05$, and Cohen's *d* effect sizes were calculated to assess magnitude of pairwise differences using the interpretation of Hopkins (Hopkins, Marshall, Batterham, & Hanin, 2009).

**Results**

Only seven of the eight pitchers were used for analysis, since one pitcher was categorised as a "submarine" pitcher (pitches the ball from the side of his body rather than overhead).

*Rate of Perceived Exertion and Ball Speed*

RPE was significantly higher at the end compared to start of the pitching session (start: 8 $\pm$ 2, end: 11 $\pm$ 3, $p$=0.04, $d$=1.48). These data suggest that pitchers felt more exerted as pitch count increased, and the magnitude of change was large. Individual pitcher RPEs are presented in Figure 1A. No significant differences were found in ball speed between the first and last pitches thrown of the simulated game (start: 82 $\pm$ 5, end: 82 $\pm$ 3, $p$=0.08, $d$=0.34). These data indicate that pitch speed was affected by increased pitch count only to a small degree. Similar start and end average pitch speeds were around 81 miles per hour, which falls within the typical ability of a NCAA Tier 2 and 3 pitchers (NSCA Athletic Recruting, 2016). Individual pitcher ball speeds are presented in Figure 1B.

*Stride Knee Joint Kinematics*

Small, non-significant differences were found in peak stride knee flexion, peak stride knee abduction, peak stride knee adduction, and peak stride knee internal rotation between the first and last pitches thrown of the simulated game (Table 1). These data suggest that 3D stride knee joint angles were minimally affected by increased pitch count. Ensemble curves for 3D knee joint angles at the start and end of the pitching outing are shown in Figures 2A-C.

*Stride Knee Joint Kinetics*

Small, non-significant differences were found in peak stride extensor moment, peak stride knee flexor moment, peak stride knee abductor moment, and peak stride knee internal rotation moment between the first and last pitches thrown of the simulated game (Table 1). In general, our results suggest that increased pitch repetition minimally alters 3D stride knee moments. Ensemble curves for 3D knee joint moments at the start and end of the pitching outing are shown in Figures 2D-F.

*Secondary Kinematic Variables*

Small, non-significant differences were found in 3D hip kinematics and kinetics between the first and last pitches (Table 2). Similar small, non-significant differences were found in 3D ankle kinematics/kinetics and stride length between the first and last pitches thrown of the simulated game (Table 2). Our data suggest that increase pitch repetition minimally alters 3D stride hip and ankle angles and moments, and stride length.

## Discussion and Implications

The purpose of this study was to assess the effects of pitch repetition on 3D stride knee kinematics and moments in collegiate baseball pitchers. In addition, to further understand potential injury mechanisms, this study also aimed to assess the effects of pitch repetition on ankle and hip biomechanics.

Contrary to our hypothesis, increased pitch repetition did not meaningfully alter peak stride knee frontal, sagittal, or transverse angles during a simulated indoor pitching outing. The small effect sizes (from 0.06 to 0.44) further supported that there were no meaningful differences between 3D joint angles from the first five pitches thrown to the last five pitches thrown. Our data for peak stride knee flexion angle are consistent with those previously reported (Chu, Fleisig, Simpson, & Andrews, 2009; Escamilla et al., 2007). While they did not measure stride knee frontal or transverse angles after pitch repetition, Escamilla et al. (2007) did find that stride knee flexion did not significantly change during a simulated indoor pitching protocol. It is important to note, however, that the pitchers in the Escamilla et al.(2007) study threw between 105 and 135 pitches. Mullaney et al. (2005) also investigated the effects of pitch repetition on upper and lower extremity muscle fatigue. Their pitchers threw on average 100 pitches during the testing session. While the only lower extremity measures Mullaney et al. (2005) collected were hip kinematics; they concluded that 100 pitches was not enough to elicit a lower extremity muscular fatigue response. The pitchers in the current study threw on average 48 $\pm$ 26 pitches during the testing session. Our data does not only confirm data of previous studies that conclude less than 100 pitches is not enough to alter knee kinematics (Escamilla et al., 2007; M. Mullaney et al., 2005), but it also suggests that 48 $\pm$ 26 pitches is not enough to alter knee kinetics.

Similarly, to the unchanged peak 3D knee joint angles, increased pitch repetition did not meaningfully alter peak stride knee frontal, sagittal, or transverse moments during a simulated indoor pitching outing. Our data for peak stride knee sagittal moments are consistent with those in previous literature (Kageyama, Sugiyama, Takai, Kanehisa, & Maeda, 2014). However, it is only consistent with that of the first five pitches thrown, as no other studies have measured stride knee moments after pitch counts of more than 10. Similar to previous research (Escamilla et al., 2007), pitchers participating in this study only pitched 15 pitches per inning. In a real game, pitchers may pitch more than 15 pitches per inning, thus increasing individual inning pitch volume as well as overall pitch volume during a pitching outing. It is plausible that the pitchers in the current study did not pitch a high enough volume to induce muscular fatigue, and therefore did not alter 3D stride knee joint kinematics and kinetics. Pitch count in our study was limited by coaching instructions, since pitchers were still in the off-season. The lower extremity plays an important role in force and power contribution during pitching (Fleisig et al., 1996; Stodden et al., 2006; Tippett, 1986b). We suspect that since no changes in lower limb joint mechanics were observed with increasing RPE, more effort from upper extremity joints may have been necessary to maintain pitch speed as pitch count increased. Increased upper extremity effort as pitch count increases may be an important contributing factor to upper body injuries in pitchers. If this hypothesis is correct, it may be important for trainers and coaches to further emphasize the importance of lower limb strength and conditioning to ensure that the lower extremity is contributing to maintaining pitch speed as pitch count increases. However, we did not measure upper body joint contributions to pitch speed but we propose that the relationship between lower and upper extremity contributions to pitch speed during a pitching outing should be investigated in more detail.

Peak knee extensor moment and peak tibial anterior shear force have been shown to occur at the same time during jump landings in women (Chappell, Yu, Kirkendall, & Garrett, 2002). Thus, peak knee extensor moment and peak tibial anterior shear force may be related but more work is needed to establish this relationship. Guido et al. (2012) hypothesised that due to movement repetition, pitch volume, and the downhill landing of the pitching motion, shear forces may occur in the connective tissues of the stride knee, which could be responsible for overuse musculoskeletal injury within the stride knee. In 2014, starting New York Yankees pitcher C.C. Sabathia underwent surgery on his stride knee (Knobler, 2014). Doctors discovered during a MRI prior to surgery that knee cartilage degeneration had been occurring. This degeneration mostly occurred on the anterior portion of the knee joint, behind the patella. While there was no change in sagittal moment, it is important to note that the potential link between tibial anterior shear force, stride knee extensor moment, and musculoskeletal injury in pitchers remains unclear.

Although knee joint biomechanics were unaffected by pitch count, RPE was increased from the start to the end of the pitching outing. This finding suggests that knee joint biomechanics may not be related to overall perceived exertion during a pitching outing. It is possible that while the pitchers subjectively reported an increase in lower extremity fatigue as pitch repetition increased, they may have felt more fatigued than they actually were due to not actively participating in a regular pitching volume like they would during the in-season. Decreased pitch speed is a common way to track increase in pitcher fatigue (Escamilla et al., 2007; Murray et al., 2001), but research disputes its reliability as a surrogate for fatigue (Crotin et al., 2014).  Crotin et al.(2014) stated that decreases in stride length were a more reliable way to determine the onset of fatigue than decreased pitch velocity. Our data showed no change in stride length from first to last pitch thrown. Although RPE was increased, unchanged average stride length and pitch speed indicate that true muscular fatigue may not have occurred in the pitchers during the pitching outing.

Fatigue may soon become a more important factor in pitching. Major League Baseball is currently exploring ways to increase the pace of play during baseball games. One way to increase pace of play was to decrease the amount of time the pitcher has to throw the ball in between pitches to 12 seconds. A study conducted by Sonne and Keir (2016) showed that decreasing the amount of rest in between pitches to 12 seconds increased muscle fatigue in eight pre-determined pitching arm muscles, thus potentially increasing injury risk. In the current study, the pitchers had 20 seconds from the time they were handed a baseball to deliver the pitch in accordance with collegiate baseball rules (Paronto, 2014). It is possible that the pitchers in the current study had enough recovery in between pitches to attenuate any residual affects lower extremity fatigue may have had on 3D stride knee kinematics and kinetics.

Although mean values were not different between the start and end of the pitching outing, it is interesting to note the high degree of variability in the relationship between pitch count and knee joint biomechanics among the pitchers. We suspected this variability may be associated with pitch count differences among pitchers (Figure 3). Due to this high variability in pitch count, we conducted post hoc correlation analyses to assess the relationship between pitch count and the change ($\Delta$) of each dependent variable. However, all analyses other than peak knee flexor moment and peak knee internal moment showed that the change in each dependent variable is not related to pitch count (Figure 3). This suggests that pitchers, even highly skilled ones, show highly individualised responses to changes in lower extremity kinematics and kinetics before and after a pitching outing. It may therefore be important for pitching coaches, athletic trainers and strength coaches to assess the individual pitcher responses to pitch count on lower limb movement behavior to more closely monitor injury risks. The negative association of peak knee flexor moment and peak internal rotation moment with increased pitch count (Figures 3F and 3H) indicates that a higher pitch count was associated with smaller changes or reductions in knee flexor and internal rotation moment. Although pitchers included in this study were from the same collegiate team, they were not all within the same training phase (i.e., off-season) as some pitchers had already completed many long pitch practices and could handle more throws. The pitchers who had received more long pitch practice until study testing (i.e., the pitchers with higher pitch count) appeared to be better prepared to resist sagittal and transverse plane knee moments than those who threw fewer pitches. This suggests that training or long pitch preparation status may be related to pitch count related changes in lower extremity joint kinetics. Studies should study this relationship more thoroughly in the future.

Hip and ankle biomechanics were also not affected by pitch repetition (Table 2). During the pitching motion, the stride leg forms a closed kinetic chain with the stride foot fixed on the ground while the upper body and torso rotates forcibly around the stride leg. Higher peak internal rotation of the hip can lead to increased knee abduction, therefore causing compression within the knee joint, ultimately causing pain (Nakagawa, Serrao, Maciel, & Powers, 2013). All pitchers participating in the study were from the same baseball team. It is possible that as a result, all pitchers had had similar exposure to lower extremity strength and conditioning training. Strong hip musculature may decrease the effects of fatigue on hip mechanics, thus decreasing the chance that hip mechanics would change with pitch count. However, strength training information was not obtained from the baseball team and this interpretation is only speculative. It may be worthwhile to investigate the relationship between muscle strength and lower limb joint kinetics in pitchers in the future.

It is important to consider the limitations of the present work. In order to collect GRF data to calculate knee joint kinetic data, the pitchers had to land flat on the force plate that had been inserted into the floor of the laboratory. Thus, the pitching mound used in the study was not the standard height of an official collegiate pitching mound. While the height of the indoor pitching mound was shorter (i.e., height of six inches) than the official collegiate mound height (height: 10 inches), the pitches still had the same equivalent drop height as they would on an official collegiate mound. However, it is not clear to what degree this difference in slope affected knee joint mechanics. While the drop height was similar, sagittal plane stride foot position was not. During games on an outdoor pitching mound, the stride foot lands on the downhill mound surface. This effectively changes the sagittal plane orientation of the foot at landing (i.e., more plantarflexed). In this study, the stride foot landed on level ground. This change in foot position could have altered knee and hip mechanics during indoor the pitching protocol compared to outdoor pitching.

**Conclusion**

The findings from the current study suggest that 3D stride knee joint kinematics and kinetics remain unchanged during a simulated pitching protocol in off-season collegiate baseball pitchers. Therefore, we propose that pitch count may not be an important factor to consider when assessing lower extremity musculoskeletal injury risk in collegiate pitchers. However, the current study did not assess injury risk, and more work is needed to understand the effects of pitch count and lower limb injury development.

# CHAPTER III

# GENERAL RECOMMENDATIONS

## 3.1 Summary

The aim of was study is to assess the effects of game-simulated pitch repetition on three-dimensional (3D) stride knee angles and moments in collegiate baseball pitchers. By doing so, researchers, clinicians, and coaches may be able to optimize career longevity by preventing lower extremity pitching injuries. The findings from the current study suggest that 3D stride knee joint kinematics and kinetics remain unchanged from the first inning pitched to the last inning pitched during a simulated pitching protocol in collegiate baseball pitchers. Therefore, pitch count may not be an important factor to consider when assessing lower extremity musculoskeletal injury risk in collegiate pitchers.

## 3.2 Recommendations for Future Research

Findings from the current study have summoned new research questions for our lab. Our data suggest that an increase in pitch count do not alter lower extremity kinetics. These unaltered lower extremity kinetics may be related to training status. However, the current study did not assess lower extremity strength. Future studies should assess lower extremity strength differences and their association with this lack of change. Posner et al. (Posner et al., 2011a) reported that 67% of all pitching injuries occur in the upper extremities. In the current study, although lower extremity mechanics were unaltered, ball speed was maintained with increased pitch count. The unchanged lower extremity joint kinetics may explain the altered upper extremity mechanics as pitch count increases

(Lyman et al., 2002). This possibly suggests that upper body effort is increased as pitch count increases. This may in part explain the high incidence of upper body injuries in baseball pitchers. The current study did not assess upper extremity mechanics in relation to changes in lower body biomechanics. Therefore, future studies should consider assessing this relationship with regards to injury risks in pitchers.

The current study opened up new doors for stride knee injury mechanisms that should be evaluated in future studies. Pitch repetition and its related fatigue affects may still play a role in stride knee injuries. Sonne and Keir (Sonne & Keir, 2016) measured the effects of reduced pitch time within an inning. They found that by reducing the amount of time a pitcher has to pitch the baseball, upper extremity fatigue levels increased. However, this phenomenon was not measured within the lower extremities. Guido et al.(Guido & Werner, 2012) stated that the high volume of pitch repetition, the downhill landing motion involved in pitching, and the shear forces the stride knee encounters may be a mechanism behind stride knee connective tissue damage. However, the current study did not assess injury risk and more work is needed to further understand the link between pitch count and injury development.

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## APPENDICES

### Appendix A: Tables

**Table 1**. Peak knee joint kinetics and kinematics for the first 5 pitches (Start) and the last 5 pitches (End) thrown (mean ± SD).

| | **Start** | **End** | ***d*** | ***p*-value** |
|---|---|---|---|---|
| Knee Flexion (°) | -55.0 ± 5.3 | -54.4 ± 5.0 | 0.12 | 0.66 |
| Knee Abduction Angle (°) | -6.4 ± 4.1 | -6.6 ± 5.5 | 0.09 | 0.83 |
| Knee Adduction Angle (°) | 5.3 ± 7.3 | 6.2 ± 5.5 | 0.16 | 0.54 |
| Knee Internal Rotation Angle (°) | 17.1 ± 4.8 | 16.8 ± 6.1 | 0.06 | 0.80 |
| Knee Extensor Moment (Nm·kg$^{-1}$) | 1.8 ± 0.4 | 1.6 ± 0.5 | 0.44 | 0.40 |
| Knee Flexor Moment (Nm·kg$^{-1}$) | -2.2 ± 0.8 | -2.2 ± 0.8 | 0.13 | 0.18 |
| Knee Abduction Moment (Nm·kg-$^{1}$) | -0.9 ± 0.4 | -1.1 ± 0.4 | 0.29 | 0.55 |
| Knee Internal Rotation Moment (Nm·kg$^{-1}$) | 0.5 ± 0.3 | 0.5 ± 0.2 | 0.10 | 0.77 |

**Table 2.** Secondary variables including ankle and hip joint biomechanics and stride length for the first 5 pitches (Start) and the last 5 pitches (End) thrown (mean ± SD).

| | **Start** | **End** | ***d*** | ***p*-value** |
|---|---|---|---|---|
| Stride Length (m) | 1.3 ± 0.1 | 1.3 ± 0.1 | 0.00 | 1.00 |
| Hip Flexion (°) | 88.0 ± 7.6 | 85.2 ± 8.6 | 0.38 | 0.13 |
| Hip Adduction Angle (°) | 9.6 ± 9.8 | 8.4 ± 13.6 | 0.11 | 0.66 |
| Hip Internal Rotation Angle (°) | 13.0 ± 6.8 | 13.8 ± 10.5 | 0.10 | 0.66 |
| Hip Extensor Moment (Nm·kg$^{-1}$) | -1.7 ± 1.0 | -1.6 ± 1.3 | 0.10 | 0.49 |
| Hip Flexor Moment (Nm·kg$^{-1}$) | 1.6 ± 0.4 | 1.5 ± 0.5 | 0.33 | 0.45 |
| Hip Abduction Moment (Nm·kg$^{-1}$) | -0.6 ± 0.2 | -0.5 ± 0.3 | 0.19 | 0.63 |
| Hip Adduction Moment (Nm·kg$^{-1}$) | 0.3 ± 0.2 | 0.3 ± 0.2 | 0.00 | 0.94 |
| Ankle Eversion Angle (°) | -1.2 ± 4.9 | -2.1 ± 5.1 | 0.20 | 0.29 |
| Ankle Abduction Moment (Nm·kg$^{-1}$) | -0.2 ± 0.2 | -0.3 ± 0.2 | 0.41 | 0.17 |

## Appendix B: Figures

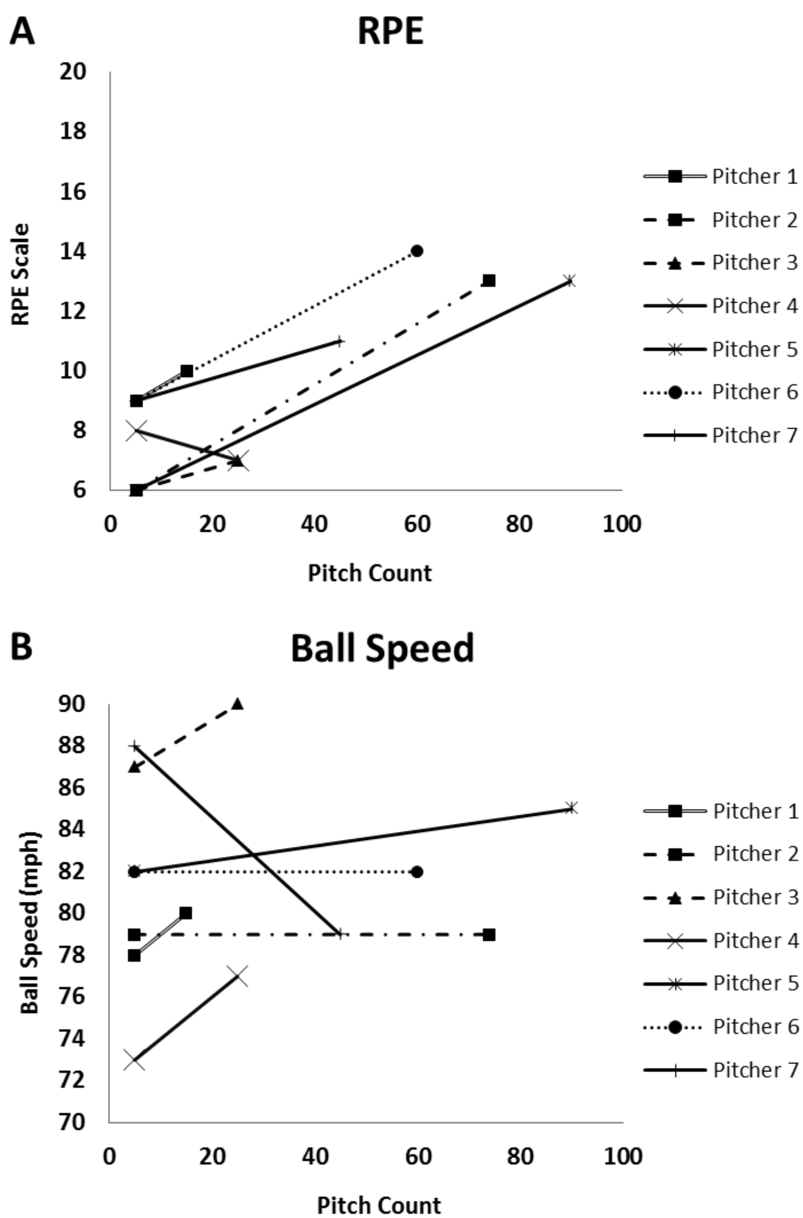


**Figure 1.** Individual pitcher data for RPE (A) and Ball Speed (B) from start to end of the pitching protocol.

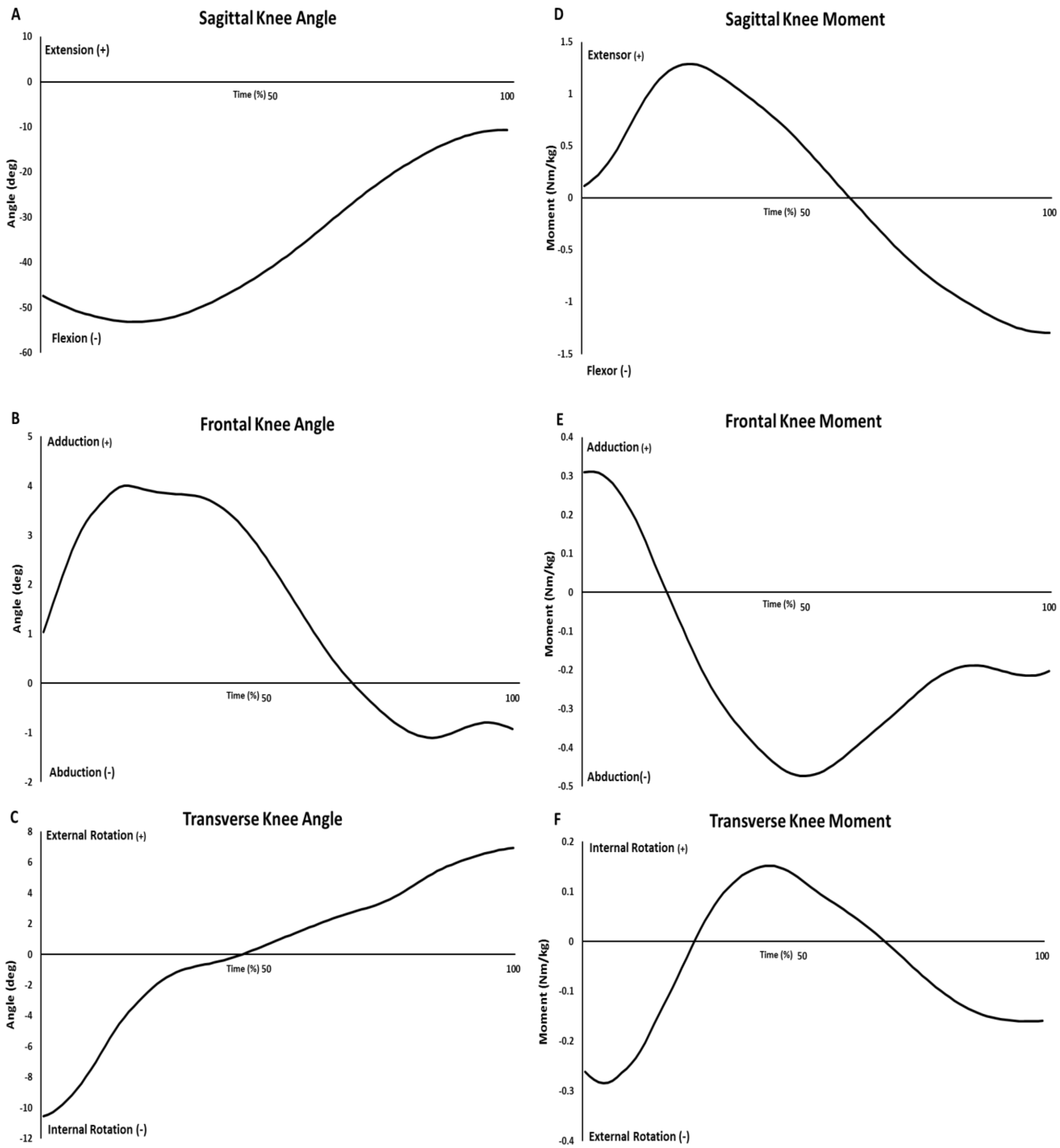


**Figure 2.** Group mean ensemble curves for 3D knee joint angles (A-C) and 3D knee joint moments (D-F) at the start and end of the pitching outing.

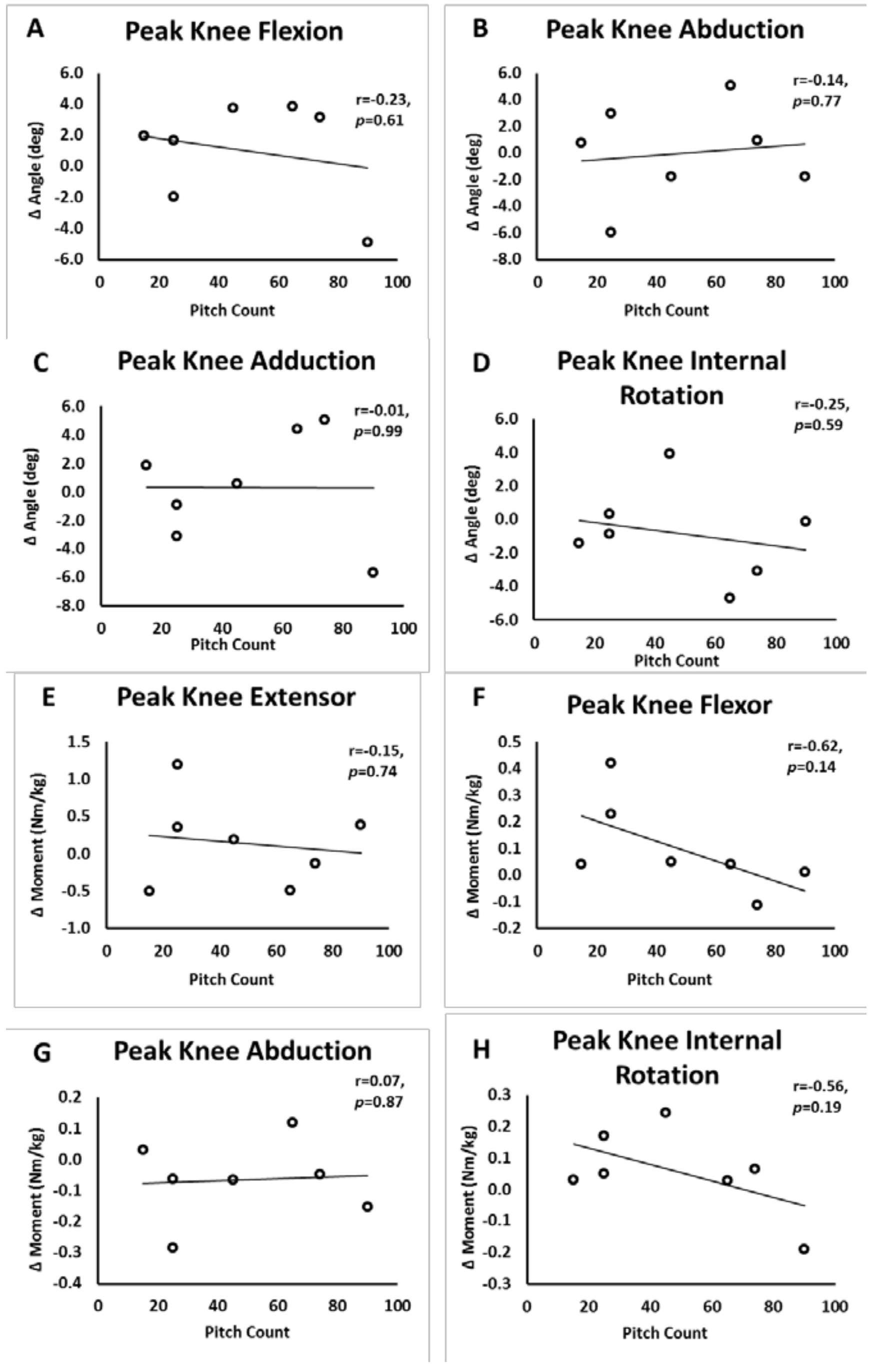


**Figure 3.** Pearson's r correlations (A-H) to assess the relationship between pitch count and the change (Δ) of each dependent variable.

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# Appendix C: Consent Form

## Consent to Participate in a Research Study

***Effects of Game-Simulated Pitch Repetition on Knee Joint Kinetics in Collegiate Baseball***

### WHY ARE YOU BEING INVITED TO TAKE PART IN THIS RESEARCH?

You are being invited to take part in a research study assess the effects of baseball pitch repetition on how your legs move. You are being invited to take part in this research study because you are a NCAA Division I collegiate baseball pitcher. In addition, you are being invited because you are not currently injured, have not been injured within the past six months, and have never undergone any lower extremity surgeries. If you volunteer to take part in this study, you will be one of about ten people to do so at the University of Memphis.

### WHO IS DOING THE STUDY?

The person in charge of this study is Shelby Peel, a Graduate Assistant in the The School of Health Studies at the University of Memphis. She is being guided in this research by her thesis advisor, Dr. Max Paquette. There may be other people on the research team assisting at different times during the study.

### WHAT IS THE PURPOSE OF THIS STUDY?

The purpose of the study is to see how baseball pitch repetition changes ankle, knee and hip motion in collegiate baseball pitchers. With the results, we hope to further understand potential factors that cause injuries.

### ARE THERE REASONS WHY YOU SHOULD NOT TAKE PART IN THIS STUDY?

We will be recruiting NCAA Division I baseball pitchers who currently are injury free, have been injury free for the past six months, who have never undergone any lower extremity surgeries, and who pitch more than three innings in an outing. If these criteria do not apply to you, then we apologize, but you cannot participate in the study.

### WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST?

The research testing will be conducted at in the Musculoskeletal Analysis Laboratory (Fieldhouse 171) at The University of Memphis. You will need to come to the lab for one testing session during one of your long pitch practices. This session will last approximately 1.5 to 2 hours.

### WHAT WILL YOU BE ASKED TO DO?

During the testing session, you will be informed of all procedures, potential risks, and benefits associated with the study through both verbal and written form. We will also record your height and weight. Reflective markers (plastic spheres) will be placed on your legs and pelvis to track motion during pitching. You will then be asked to complete any pre-game warm up and stretching

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that you would normally do before a game. After warm up, you will then complete a six-inning simulated pitching outing. You will be given the appropriate amount of time for pre-game preparations and warm-up. You will be asked to throw 15 maximal effort pitches per inning. Once handed a baseball, you will have a maximum of 20 seconds to deliver the pitch in accordance with current collegiate baseball rules. You will be asked to throw a variety of pitches during your inning (e.g. fastball, curveball, change-up, slider). You will be asked to rank your level perceived overall fatigue using a Borg's Perceived Exertion Scale. In addition, you will be asked to rate muscular fatigue of the knee extensors, knee flexors, hip adductors, hip abductors, hip extensors, plantarflexors, and dorisflexors after each simulated inning. A radar gun (Striker Sports Radar, Plano, Texas) will also be used to record pitch speed and to ensure high motivation through knowledge of results. Prior to the sixth inning, if you feel as if you have reached fatigue and can no longer pitch with proper pitching mechanics, the testing session will stop.

**WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?**

The potential risks and discomforts that may be experienced are minimal and not outside of what you would experience during a long pitch practice.

**WILL YOU BENEFIT FROM TAKING PART IN THIS STUDY?**

There may not be any direct benefits from participating in this study. The participants in this study will receive information regarding the changes in leg movements before and after a pitching outing. We expect the findings of this study will provide further insight for potential lower extremity injury mechanisms during pitching.

**DO YOU HAVE TO TAKE PART IN THE STUDY?**

If you decide to take part in the study, it should be because you really want to volunteer. You will not lose any benefits or rights you would normally have if you choose not to volunteer. You can stop at any time during the study and still keep the benefits and rights you had before volunteering. As an athlete, if you decide not to take part in this study, your choice will have no effect on your athletic status with the team.

**IF YOU DON'T WANT TO TAKE PART IN THE STUDY, ARE THERE OTHER CHOICES?**

If you do not want to be in the study, there are no other choices except not to take part in the study.

**WHAT WILL IT COST YOU TO PARTICIPATE?**

There are no costs associated with taking part in the study except for your full commitment to the timeframe of the study.

**WILL YOU RECEIVE ANY REWARDS FOR TAKING PART IN THIS STUDY?**

You will not receive any compensation for taking part in the study.

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**WHO WILL SEE THE INFORMATION THAT YOU GIVE?**

We will make every effort to keep private all research records that identify you to the extent allowed by law. Your information will be combined with information from other people taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. You will not be personally identified in these written materials. We may publish the results of this study; however, we will keep your name and other identifying information private. The information on the forms we will have you fill out will remain private, and only the study staff will see them.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. After the forms you will fill out are completed, they will be kept in a locked file cabinet at which my research team will be the only ones to be able to access it. Any information that is transferred electronically will be stored on a computer with passcode entry that only the research team will know.

We will keep private all research records that identify you to the extent allowed by law. However, there are some circumstances in which we may have to show your information to other people. If any medical situation arises at which the paramedics or any other form of emergency care have to be called, we may be required to provide health history forms and/or contact information. Also, the law may require us to show your information to a court or to tell authorities if you report information that could pose a danger to yourself or someone else. Also, we may be required to show information which identifies you to people who need to be sure we have done the research correctly; these would be people from such organizations as the University of Memphis or any funding agencies that may have ties with our research study.

**CAN YOUR TAKING PART IN THE STUDY END EARLY?**

If you decide to take part in the study you still have the right to decide at any time that you no longer want to continue. You will not be treated differently if you decide to stop taking part in the study.

The individuals conducting the study may need to withdraw you from the study. This may occur if you are not able to follow the directions you are given or if we find that your being in the study presents a greater risk than benefit to you. Your withdrawal would result in the power of the study to go down, and may require the researchers to find a replacement subject if the time permits.

**ARE YOU PARTICIPATING OR CAN YOU PARTICIPATE IN ANOTHER RESEARCH STUDY AT THE SAME TIME AS PARTICIPATING IN THIS ONE?**

You may take part in this study if you are currently involved in another research study. As long as the current study you are participating in does not require you to perform strenuous exercise that may change how you would normally pitch, then you should be able to partake in multiple studies, once discussed with the researcher. It is important to let the investigator/your doctor know if you are in another research study. You should also discuss with the investigator before you agree to participate in another research study while you are enrolled in this study.

**WHAT HAPPENS IF YOU GET HURT OR SICK DURING THE STUDY?**

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If you believe you are hurt or if you get sick because of something that is due to the study, you should call Shelby Peel at (901) 678-5388 immediately. If it is an emergency that requires medical attention please call 911.

If abnormal signs or symptoms are present during your participation, testing will be terminated and you will receive attention, following the Adverse Events plan of the Musculoskeletal Analysis Laboratory. Otherwise, no treatment will be provided.

It is important for you to understand that the University of Memphis does not have funds set aside to pay for the cost of any care or treatment that might be necessary because you get hurt or sick while taking part in this study. Also, the University of Memphis will not pay for any wages you may lose if you are harmed by this study.

Medical costs that result from research related harm cannot be included as regular medical costs. Therefore, the medical costs related to your care and treatment because of research related harm will be your responsibility. A co-payment/deductible from you may be required by your insurer or Medicare/Medicaid even if your insurer or Medicare/Medicaid as agreed to pay the costs. The amount of this co-payment/deductible may be substantial.

You do not give up your legal rights by signing this form.

**WHAT IF YOU HAVE QUESTIONS, SUGGESTIONS, CONCERNS, OR COMPLAINTS?**

Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions, suggestions, concerns, or complaints about the study, you can contact the investigator, Shelby Peel sapeel@memphis.edu, her advisor Dr. Max Paquette at mrpqette@memphis.edu, or come by the researcher's office located in FH 158.

If you have any questions about your rights as a volunteer in this research, contact the Institutional Review Board staff at the University of Memphis at 901-678-2705. We will give you a signed copy of this consent form to take with you.

**WHAT IF NEW INFORMATION IS LEARNED DURING THE STUDY THAT MIGHT AFFECT YOUR DECISION TO PARTICIPATE?**

If the researcher learns of new information in regards to this study, and it might change your willingness to stay in this study, the information will be provided to you. You may be asked to sign a new informed consent form if the information is provided to you after you have joined the study.

______________________________________ ____________
Signature of person agreeing to take part in the study Date

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________________________________________
Printed name of person agreeing to take part in the study

________________________________________ ____________
Name of [authorized] person obtaining informed consent Date

## Appendix D: IRB Approval

The University of Memphis Institutional Review Board, FWA00006815, has reviewed and approved your submission in accordance with all applicable statuses and regulations as well as ethical principles.

**PI NAME:** Shelby Peel
**CO-PI:**
**PROJECT TITLE:** Effects of Game-Simulated Pitch Repetition on Knee Joint Kinetics in Collegiate Baseball Pitchers
**FACULTY ADVISOR NAME (if applicable):** Maxime Paquette

**IRB ID:** #3873
**APPROVAL DATE:** 10/09/2015
**EXPIRATION DATE:** 10/09/2016
**LEVEL OF REVIEW:** Expedited
*Please Note: Modifications do not extend the expiration of the original approval*

Approval of this project is given with the following obligations:

1. If this IRB approval has an expiration date, an approved renewal must be in effect to continue the project prior to that date. If approval is not obtained, the human consent form(s) and recruiting material(s) are no longer valid and any research activities involving human subjects must stop.

2. When the project is finished or terminated, a completion form must be completed and sent to the board.

3. No change may be made in the approved protocol without prior board approval, whether the approved protocol was reviewed at the Exempt, Expedited or Full Board level.

4. Exempt approval are considered to have no expiration date and no further review is necessary unless the protocol needs modification.

Approval of this project is given with the following special obligations:

Thank you,

Thank you,

James P. Whelan, Ph.D.

Institutional Review Board Chair

The University of Memphis.