THE INFLUENCE OF LOWER EXTREMITY MUSCLE FATIGUE ON BASEBALL PITCHING BIOMECHANICS AND PERFORMANCE

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Baseball pitching is a complex and dynamic movement involving the lower extremities, trunk, and upper extremities with the goal of throwing the 145 g baseball toward home plate with maximal velocity and accuracy. Previous research has shown a link between elbow and shoulder injury with increased pitch volume, innings pitch in a calendar year, pitch type, and number of months pitched per year (21,32). According to Spotrac, which records the injured list of MLB players and their salaries while on the injured list, 18,369 days were missed by MLB pitchers on the injury list with a throwing-related injury in 2019, which translates into $318,667,058 lost by MLB clubs (35). To date, multiple studies that have investigated the influence of fatigue on pitching kinetics, kinematics, and muscle activation in the different phases of the pitching motion (2,3,8, 24,27,28). However, none of these studies consider the performance aspects of pitching accuracy as well as pitching velocity in a simulated baseball pitching performance in which joint kinematics and muscle fatigue are also recorded. **PURPOSE:** The purpose of this study is to determine how lower extremity fatigue with increased pitch count impacts a pitcher's joint kinematics, muscle activation levels, and pitching performance so that coaches may better be able decide when to take a pitcher out of a game. **METHODS:** Eleven high school and collegiate pitchers (age: 16.67 ± 0.86 years, height: 1.78 ± 0.08 m, weight: 74.6 ± 14.82 kg) with 11.4 ± 1.59 years of experience participated, two of which had to be excluded due to EMG issues. Data were collected using Noraxon Ultium Lab EMG, IMU, and Ninox 120 video camera. EMG electrodes were equipped to muscle bellies of the stride leg (BF, GAST, SEMI, VL, VM) and drive leg (GM, VL, VM) muscles, with IMU's being equipped to the stride leg (shank and thigh) and throwing shoulder (upper arm and forearm), along with C7. After a warmup, participants were equipped with EMG and performed MVIC testing, and then equipped with IMU. IMU were then calibrated, and participants were given the opportunity to thrown warmup pitches off the mound. Participants threw 14-18 pitch innings with fastball, offspeed, and breakingball randomized like a game scenario. Participants threw a minimum of 60 pitches with a maximum of 105 pitches thrown. After each inning, participant rating of perceived exertion (RPE) was recoded. **RESULTS:** Participants averaged 80 ± 13 total pitches and had a pitch velocity of (fastball 73.29 ± 5.98 mph, 73.76 ± 6.08 mph, offspeed 66.30 ± 5.98 mp, 66.41 ± 6.25 mph, and breakingball 62.81 ± 5.44 mph, 62.87 ± 5.63 mph) and pitch accuracy of (fastball 41.17 ± 25.48%, 37.63 ± 19.67%, offspeed 38.71 ± 30.87%, 28.77 ± 19.43%, and breakingball 30.24 ± 21.70%, 28.90 ± 20.86%) for the first and last innings respectively. Shoulder external rotation for the follow through phase of the pitching motion was significantly different from the first to last inning (p=0.03). There were no other variables that were found to be significantly different from first to last inning **CONCLUSION:** From the first to last inning, participant median frequency (Hz) for EMG did not significantly change, thus we do not believe that their lower extremity muscles were fatigued. However, we did notice that with no lower extremity fatigue, there were moderate Cohen's D for effect size of the Wind Up and SFC pitching phase for throwing shoulder external rotation. This would indicate that although there was so significant difference, in the Wind Up and SFC phases there were moderate differences in the mean from first to last inning. Overall, this suggests that future studies should investigate how many pitches it takes for a pitcher to fatigue.

The Influence of Lower Extremity Muscle Fatigue on Baseball Pitching Biomechanics and Performance

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Chapter 1 - Introduction

Baseball is a popular sport in the United States; across all divisions in the National Collegiate Athlete Association (NCAA) it is top three in participation. The NCAA has reported 941 teams with 38,466 athletes participating in men's baseball during the 2021-22 season (36). Baseball pitching is a complex and dynamic movement involving the lower extremities, trunk, and upper extremities with the goal of throwing the 145 g baseball toward home plate with maximal velocity and accuracy. It is generally understood that to achieve maximum throwing velocity, the pitcher must utilize the lower extremities in an explosive, forceful, and efficient manner. Since baseball pitching is a very explosive movement with rapid acceleration and deceleration of the lower and upper extremities, it may place athletes at a higher risk for elbow and shoulder injuries with increased pitch count. Previous research has shown a link between elbow and shoulder injury with increased pitch volume, innings pitch in a calendar year, pitch type, and number of months pitched per year (28,39). For Major League Baseball (MLB) organizations, the costs associated with pitcher throwing-related injuries are extreme. According to Spotrac, which records the injured list of MLB players and their salaries while on the injured list, 18,369 days were missed by pitchers on the injury list with a throwing-related injury in 2019, which translates into $318,667,058 lost by MLB clubs (45).

Current Major League Baseball (MLB) statistics indicate that the typical starting pitcher (SP) averages about 15 pitches per inning pitched (32). Therefore, over a typical 7 innings pitched, a starting pitcher would throw 105 pitches in a game. This is notable as the more pitches thrown, the more a pitcher will begin to fatigue, and performance will decline (18). Thus, understanding the role that fatigue plays in relation with the lower extremities in pitching performance and injury prevention is vital (6). This is seen as the more the lower extremity muscles fatigue, pitchers have more pain, and pitch with a lower pitching velocity as the pitch number increases (18).

To date, multiple studies that have investigated the influence of fatigue on pitching kinetics, kinematics, and muscle activation in the different phases of the pitching motion (6,8,13, 31,34,35). However, none of these studies consider the performance aspects of pitching accuracy as well as pitching velocity in a simulated baseball pitching performance in which joint kinematics and muscle fatigue are also recorded.

To understand how the body is used to achieve maximum throwing velocity, the phases of the pitching motion must be taken into consideration. The pitching motion can be separated into 6 distinct phases: windup, stride, arm cocking, arm acceleration, arm deceleration, and follow-through. In each phase of the pitching motion, the joint kinematics and muscle activation levels can be recorded to determine what is needed to increase performance and deter injury. Pitching phases of the stride, arm cocking, and arm acceleration phases are known to be the most important when evaluating pitcher performance, pitcher kinematics, and lower extremity muscle activation. The stride phase begins at maximal stride leg knee height after both hands have slightly separated and the pitcher's body begins the descent along the same plane of the pitching mound, it ends at stride foot contact (SFC) with the ground (6). The stride phase may most important as this is when the pitcher shifts their center of gravity (COG) towards their target and begins to utilize their lower extremity musculature. Through variations of the stride phase, the pitcher will shift their COG uniquely to maximize their pitching mechanics and gravity. Gluteus maximus activation levels of the stride leg in pitchers have been seen to be 70-100+% their MVIC in the stride and arm cocking phases of the pitching motion (6,37,38). Gastrocnemius muscle activation in the stride leg in pitchers is typically 60-140% MVIC in the stride and arm cocking phases of the pitching motion (6).

The arm cocking phase begins at stride foot contact (SFC) and ends with maximum external rotation (MER) of the throwing shoulder (4). In this phase, the stride leg will move from a more flexed position at SFC to a more extended position at MER of the throwing shoulder (4). This is critical for improved throwing velocity, as force imparted by the stride leg against the direction of the throw appears to contribute strongly to achieving maximum throwing velocity, allowing for a better transfer of force from the stride leg at SFC to ball release with a more extended stride leg (31). With an increased pitch count, maximum shoulder external rotation decreases and may negatively influence pitcher's ball velocity. Next, the arm acceleration phase is initiated with MER of the throwing shoulder and ends with ball release (4). During the arm acceleration phase, the stride leg musculature continues to stabilize the hip, knee, and ankle as center of gravity continues to move forward over the stride leg (29). At the instance of ball release, the average stride leg knee angle is around 140° of extension in reference to maximum knee extension being 180° (33). The stride leg then continues to progress into further knee extension throughout the pitching motion even after ball release (19). During this phase however, the trail leg musculature does not provide much importance as it is off the ground until the pitcher finishes the pitch and is in a position to field the baseball (6).

When evaluating the performance of the pitcher in game-situations or practice-situations, pitch accuracy and velocity are typically recorded as they can determine readiness to pitch and performance level. Pitch velocity is often the first performance metric used to evaluate a pitcher and their level of performance. Elite baseball pitchers are consistently able to produce higher fastball pitch velocities typically greater than 75 mph. During SFC and at the moment of ball release, a more extended strid leg knee has been shown to generate greater throwing velocities. Matuso et al. (2001) suggested that stabilizing or extending the stride leg during SFC helps to transfer force from the lower extremities through the body until ball release. When examining the relationship between knee angle and throwing velocity, Dowling et al. found that the greater the throwing velocity, the greater the extension of the stride leg ($P < 0.001$), indicating that knee angle is a predictor of throwing velocity at SFC. However, Solomito et al. found that knee angle had no significance when predicting throwing velocity. At SFC, knee angle showed to have no statistical significance ($P = 0.704$) on throwing velocity (34). Ultimately, with the increase in number of pitches thrown, throwing velocity decreases from the first to last innings pitched (17,27,48).

Another performance metric often viewed when evaluating pitching performance is pitching accuracy, or the pitcher's ability to throw the baseball to the targeted pitching zone over home plate. Manzi et al. reported that when comparing high-accuracy pitchers and low-accuracy pitchers, the low-accuracy group showed a significantly greater lead knee flexion at maximum throwing shoulder external rotation (P=0.028) and ball release (P=0.023). However, when pitchers throw 90+ pitches in a performance, there has been no significant difference between the accuracy recorded in the first and last innings of the performance (30,37).

Although maximum external rotation of the throwing shoulder is vital for throwing velocity, it is also a potential source of injury as the rotator cuff muscles on the back of the shoulder may become pinched in the shoulder joint (16). Sports medicine professionals reported that fatigue reduces the pitcher's ability to reach maximum external rotation (MER) of the throwing shoulder in the late cocking phase and has been shown to reduce knee flexion angle at ball release, negatively affecting ball velocity (20,34,35). Murray et al. collected kinematic data from a pool of 75 players in which seven players met the criteria of pitching a minimum of five innings. Five participants threw five innings, and the other two participants threw six innings. Murray et al. focused particularly on the kinematics of the baseball pitcher from the first inning of pitching until the last inning of pitching. Particularly investigating throwing shoulder maximum external rotation (°) and knee angle (°) at ball release along with pitching velocity. They found that Ball Velocity (mph), Maximum external rotation of the shoulder (°), and Knee angle (°) at ball release all decreased significantly ($P = 0.009$, $P = 0.007$, and $P = 0.024$) from the first inning to the last inning when pitching in the actual game. Grantham et al. reported a significant decrease ($P= 0.002$) in maximum shoulder external rotation by 2.3° from the first inning into the last inning when the pitcher was in the ball release phase of the pitching motion (24).

With an increased pitch count, muscle fatigue of the lower extremities and upper extremities sets in, and performance may be negatively impacted. The concept of muscle fatigue may be due to acute or chronic effects that may impair motor performance and is not the result of a single mechanism, rather fatigue occurs due to a host of various factors. Factors influencing performance during muscle fatigue are dependent on the conditions of the task being performed. These conditions include participant motivation, intensity and duration of the activity, the speed and type of contraction (concentric, eccentric, isometric), and the extent to which the activity is sustained (16).

To first evaluate muscle activation levels throughout a pitching performance, a Maximal Voluntary Isometric Contraction (MVIC) should be recorded to obtain baseline muscle activation levels. The MVIC is used to normalize EMG data to specific participants, however, may not always be utilized. Tucker et al. have determined that mean EMG activity of 0% to 20%

MVIC was considered minimal muscle activity; 20% to 35% MVIC moderate activity; 35% to 50% MVIC moderately strong muscle activity, and >50% MVIC showed to be a significant amount of muscle activity (48). These muscle activation level categories can aid in determining significance of muscle activation of the lower extremities throughout the pitching performance which has previously been performed by Campbell et al., along with Oliver and Keeley. Campbell et al. investigated 5 lower extremity muscles (biceps femoris (BF), rectus femoris (RF), gluteus maximus (GM), vastus lateralis (VM), and gastrocnemius (GAST)) in their defined four phases of the pitching motion. They found that phases three and four demonstrate the greatest muscle activation levels in the pitching motion. This would indicate that from stride foot contact (SFC) to ball release in phase three and ball release to 0.5 seconds after ball release (i.e., follow-through) in phase four, the greatest muscle activation levels in the pitching motion are demonstrated in the stride leg. Therefore, it is assumed that the musculature of the stride leg will fatigue and influence pitching mechanics along with pitching performance (6).

The concept of muscle fatigue may be due to acute or chronic effects that may impair motor performance and is not the result of a single mechanism, rather fatigue occurs due to a host of various factors. Factors influencing performance during muscle fatigue are dependent on the conditions of the task being performed. These conditions include participant motivation, intensity and duration of the activity, the speed and type of muscle contraction (concentric, eccentric, isometric), and the extent to which the activity is sustained (11). The task itself may influence the fatigue mechanisms of the central nervous system (CNS) drive to motor neurons, the muscles and motor units that are activated, neuromuscular propagation, and the firing rates of active motor units. Another phenomenon observed is the decline in activity of fast-twitch muscle fibers with repeated activities. Since slow twitch fibers are oxidative fibers, they are always recruited first and require the most oxygen and may sustain activity for longer periods of time compared to fast twitch fibers. As fast twitch fibers are more glycolytic fibers and require high forces to be recruited but fatigue faster, overtime, with central fatigue there is a limit to the number and firing rate of motor units that are recruited. Peripheral fatigue is another factor that may influence muscle activity and function.

Muscle fatigue has been examined when having participants perform maximum voluntary contractions (MVC's), in which the participant performs an isometric muscle contraction for 5-7 seconds and then examining the force correlated to that MVC. However, this would be difficult to determine when performing dynamic movements, thus the rate of motor unit activation may be more appropriate to discuss when examining fatigue.

Changes in the muscle force during fatigue may result in alterations of the number of motor units recruited or in the modulation of their firing rates (12). This can be shown by observing the motor unit discharge frequency. When processing EMG signals, time and frequency domains are utilized. By using an EMG power spectrum, it is known that with the introduction of muscle fatigue, there will be a left shift when there is a decrease of frequency over contraction time (1). This would indicate a decrease in the high-frequency and increase in low-frequency components. The high-frequency component occurs during adequate muscle force. The increase in low-frequency components is because the conduction velocity of the motor action potentials on the muscle membrane decreases (1).

There are varying methods to analyze EMG, typically either done by mean frequency (MF) or median frequency (MDF). Mean frequency is the average frequency of the calculated sum of the product of the EMG power spectrum and the frequency divided by the total sum of the power spectrum. The median frequency is the frequency at which the EMG power spectrum is divided into two regions of equal amplitude (38). Median frequency analysis appears to be best suited for dynamic movements according to Stulen and De Luca, as the estimation of performing a median frequency analysis is less affected by random noise and more affected by muscular fatigue (44). It has been generally recommended to process raw EMG data when evaluating median frequency as the raw data may be best to evaluate the entirety of the information as well as noise captured that can later be filtered out (44).

When evaluating muscular fatigue throughout a pitching performance, knee flexion angle has shown to be a kinematic measurement that can indicate fatigue (6,8,9). Knee flexion angle is often defined as increased amount of knee flexion from zero degrees of knee extension. As pitchers throw more pitches, the risk of injury not only increases (16,19,42), but knee flexion angle increases with less knee extension being present. This increase in knee flexion angle is not only seen chronically in a pitching performance, but also acutely during short pitching performances. Knee flexion angle has been shown to affect pitching velocity and accuracy, as the more knee flexion of the stride leg a pitcher elicits, the lower their throwing velocity (10,31,44) and a decrease in their pitching accuracy will be seen (30). Lower extremity fatigue has also shown to alter the knee angle of individuals in other aspects of motion. Barbieri et al. performed a study in which individuals stepped down from a curb pre-fatigue and post-fatigue. Results indicated statistical significance (P = 0.001) between the pre- and post-fatigued conditions, in which there was an increase in knee flexion angle of about 11° to 13° between different stepping positions.

Knowledge of both joint kinematics and muscle activation levels in the pitching motion are keys to understanding how baseball pitchers may increase pitching performance and decrease the likelihood of injury while pitching.

Purpose

The purpose of this study is to determine how lower extremity fatigue with increased pitch count impacts a pitcher’s joint kinematics, muscle activation levels, and pitching performance so that coaches may better be able decide when to take a pitcher out of a game.

Hypothesis

It is hypothesized that with increased pitch count, there will be a decrease in the EMG median frequency values, there will be a decrease in throwing shoulder external rotation, stride leg knee flexion angle will increase, pitcher throwing velocity will decrease, and changes will be seen in accuracy.

Significance

By determining if there are visual representations of fatigue, coaches will be able to better understand when to remove pitchers from their pitching performance. This may lead to better performance metrics if pitchers are able perform in game at their highest level with little to no fatigue. This study may help to understand how muscular fatigue impacts performance and injury risk; however, injury risk will not be definitively determined.

Operational Definitions

Knee Flexion Angle (KFA) – Defined as the amount of knee flexion from zero degree of maximal knee extension.
Throwing Shoulder External Rotation (ER) – Defined as 90 degrees to 180 degrees in the posterior frontal plane.
Maximal ball velocity – the greatest pitching velocity to which the pitcher can throw a fastball.
Accuracy – Extent to which the pitcher can consistently throw strikes to the 3 x 3 target strike zone as established in the Methods section.

Delimitations

Participants will be required to be actively pitching in season. However, we will not confirm that they are actively pitching other than their own confirmation.

Limitations

Participants may not give maximum effort for every pitch thrown, we cannot accurately judge effort level but will use fastball pitch velocity and Borg’s RPE scale for self-reported effort levels. Limited to high school and collegiate baseball pitcher population in the community. Participant level of conditioning will not be assessed beforehand.

Chapter 2 - Review of Literature

Baseball pitching is a complex and dynamic movement involving the lower extremities, trunk, and upper extremities with the goal of throwing the 145 g baseball toward home plate with maximal velocity and accuracy. It is generally understood that to achieve maximum throwing velocity, the pitcher must utilize the lower extremities in an explosive, forceful, and efficient manner. Since baseball pitching is a very explosive movement with rapid acceleration and deceleration of the lower and upper extremities, it may place athletes at a higher risk for elbow and shoulder injuries with increased pitch count. Previous research has shown a link between elbow and shoulder injury with increased pitch volume, increased innings pitch in a calendar year, pitch type, and number of months pitched per year (28,39). Therefore, to better understand pitching biomechanics and performance, the phases of the pitching motion, joint kinematics, muscle activation, pitch velocity, and pitch accuracy will be considered and reviewed with increased pitch count in a simulated game situation.

The Workload Aspects of Pitching

In accordance with MLB.com statistics, Major League Baseball (MLB) pitchers with the top pitches per innings pitched (PPIP) rate, typically average fewer than 15 pitches per inning (32). A starting pitcher at this rate would be able to pitch seven innings on around 105 pitches thrown in game. This pitch count can be due to various obstacles including game situation or pitcher exhaustion. Muscular exhaustion is often determined in participants having completed an average of 7 ± 2 innings or throwing an average of 99 ± 29 pitches per game (34). Erickson et al. performed a fatigue study in adolescent baseball pitchers aged 13 to 16 in which they had participants throw in a “simulated game”. Each pitcher threw 90 pitches, split between 6 innings, for 15 pitches per inning and then threw 10 warm up pitches before each inning, so there was a total of 150 pitches thrown for each pitcher (13). In a study by Yanagisawa et al., changes in lower extremity function and pitching performance with increasing pitch numbers were investigated. In this study, eighteen collegiate pitchers threw 117 pitches in 9 innings (avg = 13 per inning/ 9 fastballs and 4 curveballs) from the stretch position with 5 min rest in between innings in a simulated game (49).

Hirayama et al. performed a study in which they examined the relationship of number of pitches to kinetic changes in baseball pitchers. They recruited a small sample size of 3 college pitchers who threw 15 pitches for 9 innings (135 total pitches). Pitchers were also given 6 minutes of rest in between innings (20). These studies and MLB statistics are notable as the more pitches thrown, the more a pitcher will begin to fatigue, and performance will decline (18,32). Thus, understanding the role that fatigue plays in relation with the lower extremities in pitching performance and injury prevention is vital (3). This is seen as the more the lower extremity muscles fatigue, pitchers have more pain, and pitch with a lower pitching velocity as pitch number increases (18). To understand how the biomechanics of the pitcher are altered with fatigue, the phases of the pitching motion must first be defined.

Phases of the Pitching Motion

The pitching motion requires a synchronized movement pattern that includes the lower extremities, trunk, and upper extremities. Through this synchronized movement, maximum throwing velocity can be achieved. The lower extremities are the primary source of force production and muscle activation for each throw and begin the process of transferring force to the baseball at ball release. During the pitching motion, stabilizer muscles of the shoulder will aid in correctly positioning the shoulder throughout the entire pitching motion (4). An indication that there is reduced strength or endurance in the shoulder stabilizer muscles is a lowering of the elbow position briefly before ball release. At the point of throwing shoulder external rotation, the shoulder typically externally rotates 50° to 180 ° (17,18,36). Knowledge of the pitching phases and biomechanics vital to maximum throwing velocity is important for decreased risk of injury and increased pitching performance.

The pitching motion can be separated into 6 distinct phases: windup, stride, arm cocking, arm acceleration, arm deceleration, and follow through. The wind-up phase begins with the initial movement of the pitcher from the windup or stretch position and ends with the stride leg at maximal knee height (18). The pitcher will use the hip, knee, and ankle muscles of the drive leg in contact with the pitching rubber to stabilize the body as they progress into the stride phase (6). Next, the stride phase begins at maximal stride leg knee height after both hands have slightly separated and the pitcher's body begins the descent along the same plane of the pitching mound. The stride phase ends at stride foot contact (SFC) with the ground (6). The stride phase may be most important as this is when the pitcher shifts their center of gravity (COG) forward towards their target and begins to utilize their lower extremity musculature.

Through variations of the stride phase, the pitcher will shift their COG uniquely to maximize their pitching mechanics and gravity. Generally, two different methods of the stride phase are found in American and Japanese baseball pitchers. In the drop and drive (DD) method, the Japanese pitchers will first lower their COG by striding forward, flexing the drive leg and lowering their gluteus maximus towards the ground, they will then push their body towards home plate until the pitch is complete. American pitchers typically utilize the tall and fall (TF) method, in which they will maintain a higher COG, allowing them to benefit from gravity by “falling”, before using their lower extremities to push their body towards home plate with the drive leg (8). The stride phase method utilized by the pitcher will not be investigated in this study, however it is important to note the use of the pitcher's COG may impact the initial muscle activation in the stride phase of the drive leg, as lower extremity muscle activation will be investigated in each of the 6 pitching phases. Gluteus Maximus activation levels of the stride leg in pitchers have been seen to be 70-100+% of their MVIC in the stride and arm cocking phases of the pitching motion (6,37,38). Gastrocnemius muscle activation in the stride leg in pitchers are typically 60-140% MVIC in the stride and arm cocking phases of the pitching motion (6).

The arm cocking phase begins at SFC and ends with maximum external rotation (MER) of the throwing shoulder (2). In the arm cocking phase, the stride leg knee will transition from a flexed position into a more extended position (4). This is critical for improved throwing velocity, as force imparted by the stride leg against the direction of the throw appears to contribute strongly to achieve maximum throwing velocity, allowing for a better transfer of force from the stride leg at SFC to ball release with a more extended stride leg (31). However, at MER, it has been found that there was a significant difference (P= 0.007) between maximum shoulder external rotation between the first inning (180°) and the last inning (172°) of play (35). This shows that with increased pitch count, maximum shoulder external rotation decreases and may negatively influence pitcher’s ball velocity.

The arm acceleration phase is initiated with throwing shoulder MER and ends with ball release (4). During the arm acceleration phase, the stride leg musculature continues to stabilize the hip, knee, and ankle as COG continues to move forward over the stride leg (29). At the instance of ball release, the average stride leg knee angle is around 140° of extension in reference to maximum knee extension being 180° (24). There was found to be a significant decrease (P=

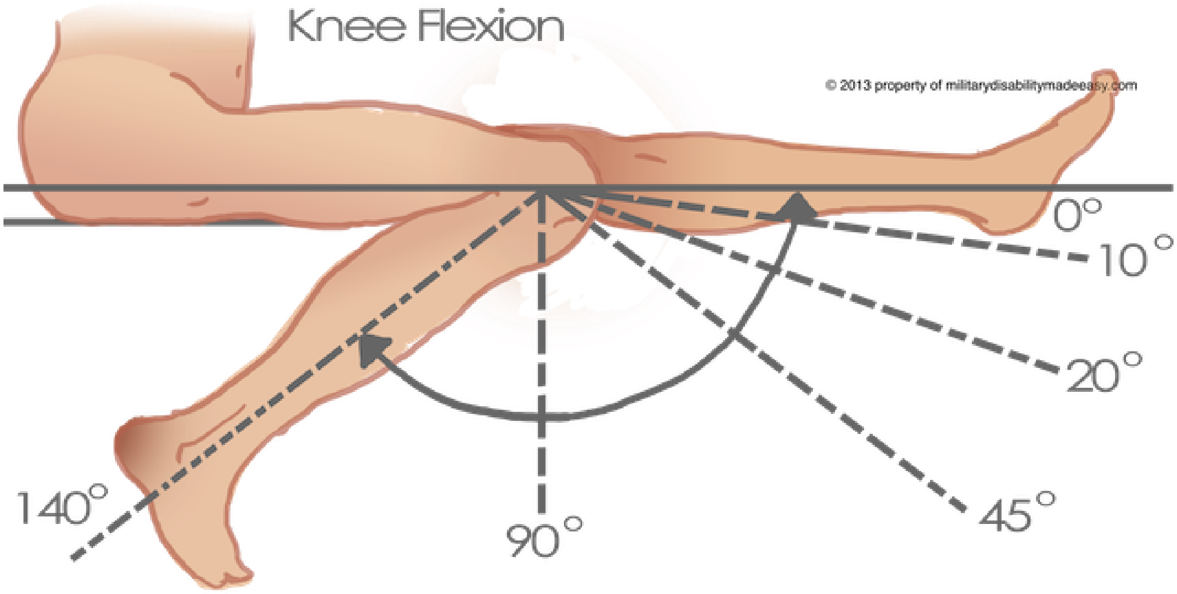
0.002) in maximum shoulder external rotation by 2.3° from the first inning into the last inning when the pitcher was in the ball release phase of the pitching motion (19). During this phase however, the trail leg musculature does not provide much importance as it is off the ground until the pitcher finishes the pitch and is able to field the baseball (6). The stride leg then continues to progress into further knee extension throughout the remaining phases of the pitching motion (19). The arm deceleration phase begins at ball release and ends with maximum throwing shoulder internal rotation (4).

During the arm deceleration and follow-through phases, the stride leg musculature maintains a dynamic single leg stance as the upper extremity continues to rotate and linearly translate over the stride leg. This is important to recognize, because the hip extensors, knee extensors, and ankle plantar flexors are highly active to dynamically control and stabilize each of the lower extremity joints (6). The follow-through phase begins with maximum throwing shoulder internal rotation and ends when the pitcher gets to a balance point or a good position to field the baseball (18).

Joint Kinematics

Kinematics refers to how the body or a joint may move through space without the consideration of force applied to the body or joints. There are various ways to determine joint kinematics, however Noraxon Ultium Portable Lab (Noraxon Inc, Scottsdale, AZ, USA) is equipped with Inertial Measurement Unit (IMU). The IMU will allow for the ability to record joint kinematics, such as joint angles, joint angular velocity, and joint accelerations of any body part or segment of interest. These joint kinematic measures will help to understand how the body is used in each phase of the pitching motion. The throwing shoulder and stride leg knee will be examined to discover how fatigue may alter pitching biomechanics with an increased pitch number.

The first joint kinematic measure that appears to be an important factor when evaluating pitching performance is the pitchers stride leg knee flexion angle. There are varying ways in which knee flexion angle is defined throughout literature. Most studies define knee flexion angle as maximum knee extension being 0°, whereas other studies define knee flexion angle as maximum knee extension as being 180°. This can be quite confusing, so knee flexion angle will be defined in relation to anatomical position. As shown below, the participant is sitting and maximum knee extension will be defined as 0°, maximum knee flexion will be described as the greatest degree to which the participant could flex the knee up to 180°.



Knee flexion angle in regard to short 8-15 pitch count performances has been recorded and appears to show that pitchers with greater throwing velocity may land at SFC with a more flexed stride leg knee (5). However, once the pitcher enters the ball release portion of the pitching motion, high-velocity pitchers will extend their stride leg knee greater than low-velocity pitchers at ball release and until the end of the pitch (10,18).

Dowling et al. performed a study in which pitchers were broken up into low- and high-velocity pitching groups. Pitchers threw 8 to 12 fastballs and were directed to throw to the middle of the target zone over home plate with maximum effort. The low-velocity group (ball velocity 36.1 ± 1.2 m/s) and high-velocity group (ball velocity 40.3 ±0.9 m/s) were compared for velocity and lead knee-extension (change in knee flexion angle from SFC to ball release). At foot contact, the low-velocity group landed with the lead knee flexed 45 ± 9° and extended the lead knee to 40 ± 14° at ball release. Conversely, the high-velocity group landed with a flexed lead knee 47 ± 8° and extended to 30 ± 14° at ball release. Ultimately, lead knee extension was found to be a significant predictor of ball velocity ($P < .001$), as the high-velocity group extended their stride leg more from SFC to ball release (10).

Kageyama et al. performed a study comparing the kinematics and kinetics of a determined low-velocity group (< 34.4 $m \cdot s^{-1}$) and high-velocity group (> 36.2 $m \cdot s^{-1}$). The high-velocity group (n=10) showed to have fastball velocity of 37.4 ± 0.8 $m \cdot s^{-1}$ and the low-velocity group (n=10) displayed a fastball velocity of 33.3 ± 0.8 $m \cdot s^{-1}$, which were both shown to be statistically significant. At SFC, the high-velocity group had a knee flexion angle of 25.5 ± 6.4° and the low-velocity group had a knee flexion angle of 26.4 ± 9.7°. It was shown the knee extension angle at SFC was greater in the high-velocity group (46.0 ± 6.7°) compared to the low-velocity group (44.2 ± 8.0°). This would help to indicate that knee flexion closer to extension and greater knee extension angle may be one of the factors that aids in greater throwing velocity (18).

The second joint kinematic measurement that appears to be correlated with pitching performance is maximum external rotation of the throwing shoulder. Previous research has shown higher throwing velocities are typically seen earlier in the pitching performance with a greater maximum shoulder external rotation (13,35). This is because with an increase in pitch count, pitch velocity and maximum shoulder external rotation both decrease (13,14,35). Maximum shoulder external rotation may also have an impact on pitch accuracy as Manzi et al. have demonstrated. They showed that the higher accuracy pitchers had about 2° to 3° more of maximum external rotation of the throwing shoulder. So, when examining multiple pitching performance studies that investigated the role of maximum shoulder external rotation, it can be said that with greater maximum external rotation of the shoulder, pitch velocity and accuracy have the potential to be positively impacted.

Muscle Activation

To understand the varying levels of lower extremity muscle activation, we must first understand how muscle activation is measured. Electromyography (EMG) is used to measure muscle response or electrical activity in response to a nerve’s stimulation of a muscle. The EMG will measure electrical activity of muscle during rest, slight contraction, and forceful contraction (17). Baseline muscle activation levels will be referenced to a Maximal Voluntary Isometric Contraction (MVIC) test that is performed before any data collection. The MVIC will help to determine at what level the muscles are activated in response to the activity. Knowledge of muscle activation levels and joint kinematics will provide a better understanding of how the lower extremities are utilized throughout the pitching motion to generate ball velocity and dynamically stabilize the body through different loading progressions in the pitching motion (6).

Muscle Activation Levels in Pitching

Campbell et al. conducted a study on the lower extremity muscle activation during pitching. In this study, electromyography (EMG) was utilized to determine the MVIC and muscle activation of 5 lower extremity muscles (biceps femoris (BF), rectus femoris (RF), gluteus maximus (GM), vastus lateralis (VM), and gastrocnemius (GAST)). The pitching motion was divided into four phases (phase 1, initiation of pitch to maximum stride knee kick height; phase 2, maximum stride leg knee height to SFC; phase 3, SFC to ball release; phase 4, ball release to 0.5 seconds after ball release (i.e., follow-through). It was found that in the stride leg in phase 1, % MVIC values are as follows BF (29± 22), GM (19 ± 10), RF (14 ± 10), VM (17 ± 13), GAST (31 ± 8). Percent MVIC values for phase 2 were recorded and listed as, BF (23 ± 10), GM (72 ± 47), RF (86 ± 55), VM (42 ± 38), GAST (66 ± 47). Phase 3 % MVIC values were seen to be BF (99 ± 64), GM (108 ± 33), RF (167 ± 38), VM (166 ± 47), GAST (140 ± 31). It was found that in phase 4, MVIC values were BF (125 ± 81), GM (170 ± 75), RF (47 ± 34), VM (89 ± 59), GAST (126 ± 63). These results indicate that phases 3 & 4 demonstrate the greatest muscle activation levels in the pitching motion. Specifically, phase 3 showed the greatest muscular activation in 3 of 5 lower extremity muscles (RM, VM, and GAST). In phase 4, both the GM (170 ± 75) and BF (125 ± 81) displayed an increased mean MVIC value when compared to the other 3 phases in the pitching motion (6). It was found that muscle activity levels of the stride leg were moderate to high during phases 2-4 (23-170% of MVIC) (6). As results indicate, there were moderate to high levels of muscle activation in the stride leg. Therefore, it is assumed that the musculature of the stride leg will fatigue and influence pitching mechanics and performance (6).

Quantifying fatigue

The concept of muscle fatigue may be due to acute or chronic effects that may impair motor performance and is not the result of a single mechanism, rather fatigue occurs due to a host of various factors. Factors influencing performance during muscle fatigue are dependent on the conditions of the task being performed. These conditions include participant motivation, intensity and duration of the activity, the speed and type of muscle contraction (concentric, eccentric, isometric), and the extent to which the activity is sustained (11). The task itself may influence the fatigue mechanisms of the central nervous system (CNS) drive to motor neurons, the muscles and motor units that are activated, neuromuscular propagation, and the firing rates of active motor units. Another phenomenon observed is the decline in activity of fast-twitch muscle fibers with repeated activities. Since slow twitch fibers are oxidative fibers, they are always recruited first and require the most oxygen and may sustain activity for longer periods of time compared to fast twitch fibers. As fast twitch fibers are more glycolytic fibers and require high forces to be recruited but fatigue faster, overtime, with central fatigue there is a limit to the number and firing rate of motor units that are recruited. If the individual is not producing enough force to continually recruit the fast twitch motor units, there is generally thought to be muscle fatigue that has set in. Peripheral fatigue is another factor that may influence muscle activity and function. Peripheral fatigue is a result of a reduction in efficacy of the neuromuscular junction and neuromuscular function as metabolic and biochemical changes within the muscle (1,29). This may be due to changes in accumulation of lactate, ATP, calcium reuptake, and cross bridge cycling (11).

Muscle fatigue has been examined when having participants perform maximum voluntary contractions (MVC’s), in which the participant performs an isometric muscle contraction for 5-7 seconds and then examining the force correlated to that MVC. However, this would be difficult to determine when performing dynamic movements, thus the rate of motor unit activation may be more appropriate to discuss when examining fatigue.

Changes in the muscle force during fatigue may result in alterations of the number of motor units recruited or in the modulation of their firing rates (12). This can be shown by observing the motor unit discharge frequency. When processing EMG signals, time and frequency domains are utilized. By using an EMG power spectrum, it is known that with the introduction of muscle fatigue, there will be a left shift when there is a decrease of frequency over contraction time (1). This would indicate a decrease in the high-frequency and increase in low-frequency components. The high-frequency component occurs during adequate muscle force. The increase in low-frequency components is because the conduction velocity of the motor action potentials on the muscle membrane decreases (1).

There are varying methods to analyze EMG, typically either done by mean frequency (MF) or median frequency (MDF). Mean frequency is the average frequency of the calculated sum of the product of the EMG power spectrum and the frequency divided by the total sum of the power spectrum. The median frequency is the frequency at which the EMG power spectrum is divided into two regions of equal amplitude (38). Median frequency analysis appears to be best suited for dynamic movements according to Stulen and De Luca, as the estimation of performing a median frequency analysis is less affected by random noise and more affected by muscular fatigue (44). It has been generally recommended to process raw EMG data when evaluating median frequency as the raw data may be best to evaluate the entirety of the information as well as noise captured that can later be filtered out (44).

Knee Flexion Angle with Fatigue

In a gait study performed by Kellis et al., 15 females (21.5 ± 2.8 years) who were middle distance runners participated in treadmill running. Muscles fatigued were the primary controllers of the knee and ankle in sagittal-plane movements. Kinematics were captured using a 3-D Vicon motion analysis system (OxfordMetrics Ltd, Oxford, UK). A Cybex Norm isokinetic dynamometer (Lumex Corporation, Ronkonkoma, NY) was utilized for fatigue testing of participants. Knee fatigue protocol range from 0° to 90° of knee flexion. The mean of 5 right steps for all kinematic parameters, pre-fatigue exercise, post-fatigue exercise was examined for each protocol used in the study. Kinematic data were normalized to 100% of the gait cycle. The angles of the thigh relative to the tibia (knee flexion-extension) during the swing phase of gait were calculated and analyzed. Knee flexion angle increased after both the pre- and post-fatigue protocols. At initial foot contact, knee flexion angle pre fatigue protocol was (15 ± 4) and the post fatigue protocol was (19 ± 6) indicating that with the introduction of fatigue during level running, knee flexion angle increases in running (27).

In a baseball pitching study, Erickson et. al recruited 29 male participants (14.6 ± 0.9 years) in which pitchers threw in a "simulated game" for a total of 150 pitches (15 pitches for each of 6 innings, 10 warmup pitches for each inning). Pitchers were told to throw at 100% maximum velocity from the windup. Erickson et al. measured velocity and accuracy, and filmed pitchers for kinematics over the course of the study for each participant. Pitchers were pre-tested for range of motion prior to any warmup. Pitchers then warmed up and performed 15 fastballs at 100% maximum velocity for each of the 6 innings they pitched. Pitchers would also warm up before each inning by throwing 10 warm up pitches. After the completion of the 90 pitches, participants performed a post-test for range of motion. Erickson et. al indicated that velocity (mph) significantly decreases (73 ± 5 mph to 71 ± 6 mph, *P*<.001) and knee flexion angle increases (49° ± 15° to 53° ± 15°, *P*=.528) at ball release with the increasing number of pitches thrown (13). Although there was no significant increase in knee flexion angle, the slight increase in knee flexion angle from the beginning of the simulated game to the end indicates that knee flexion angle should be further investigated.

Murray et al. performed a baseball pitching study in which they found similar results noting that in the first inning, knee flexion angle was 140°, in the last inning of pitching, knee flexion angle was 132°. Results indicated statistical significance (*P* = .024). This would indicate that with increased pitch count, knee flexion angle increases (35). Knee flexion angle was shown to be in reference to maximum extension being 180° rather than 0°, which shows the need for a definition of knee flexion angle.

When performing a step down from a curb study, Barbieri et al. recruited 10 healthy volunteers (27.60 ± 2.79 years) in which they evaluated muscle fatigue on the last stride before stepping down a curb. Participants performed a step-down task before and after a fatigue protocol of the knee. This fatigue protocol of the knee extensor and flexor muscles included sit-to-stand movement from a chair with arms across the chest at a frequency of 0.5 Hz controlled by a metronome. Fatigue protocol was over once the participant indicated they were unable to continue, movement frequency fell below and remained below 0.5 Hz after encouragement, or after 30 minutes. Before and after fatigue protocol, participants stepped down a 10-cm elevation. Participants were not allowed a rest period between trials and testing was started as soon as possible after fatigue protocol. To record kinematics, a 3 x 3 optical system (Optotrak Northern Digital Inc., Waterloo, Ontario, Canada) was used at a rate of 50 Hz. Knee joint angles were estimated using a 3D linked-segment model and ranges of angular motion (ROM) of the left knee joint in the sagittal plane was calculated. It was determined that pre-fatigue, the knee flexion angles were N-1 (66.34° ± 4.55°) and N-2 (66.18° ± 4.85°), whereas post knee fatigue, the knee flexion angle was determined to be N-1 (55.04° ± 13.01°) and N-2 (52.96° ± 5.47°). Although this shows a decrease in knee flexion angle, that is because these authors use the knee flexion angle in reference to knee extension. So, a decrease in knee extension angle would indicate an increase in knee flexion angle. This would represent that when presented with muscular fatigue, muscle of the knee joint will allow for an increase in knee flexion angle (3).

Throwing Shoulder ER with Fatigue

Sports medicine professionals have reported that fatigue reduces the pitcher’s ability to reach maximum external rotation (MER) in the late cocking phase and has been shown to reduce knee flexion angle at ball release, negatively affecting ball velocity (20,34,35). In a study by Murray et al., kinematic, and kinetic parameters were determined throughout the course of extended play. It was found that there was a significant difference (*P*= 0.007) between maximum shoulder external rotation between the first inning (180°) and the last inning (172°) (35). This shows that with increased pitch count, maximum shoulder external rotation decreases and may negatively influence pitcher’s throwing velocity. A study conducted by Grantham et al. reported participants pitched an average of 96.7 ± 16.1 pitches per game, or 6.3 ± 1.6 full innings. There was a mean increase of 17.8% ± 14.1% in subjective fatigue reported at the end of the games, however pitchers showed no significant decrease in pitch velocity. There was found to be a significant decrease (*P*= 0.002) in maximum shoulder external rotation by 2.3° from the first inning into the last inning when the pitcher was in the ball release phase of the pitching motion (19).

Erickson et. al recruited 29 male participants (14.6 ± 0.9 years) in which pitchers threw in a "simulated game" for a total of 150 pitches (15 pitches for each of 6 innings, 10 warmup pitches for each inning). Pitchers were told to throw at 100% maximum velocity from the windup. Erickson et al. measured velocity and accuracy, and filmed pitchers for kinematics over the course of the study for each participant. Pitchers were pre-tested for range of motion prior to any warmup. Pitchers then warmed up and performed 15 fastballs at 100% maximum velocity for each of the 6 innings they pitched. Pitchers would also warm up before each inning by throwing 10 warm up pitches. After the completion of the 90 pitches, participants performed a post-test for range of motion. It was reported that maximum shoulder external rotation decreased from the first (184° ± 12°) to the last (181° ± 20°) inning in the cocking phase of the pitching motion (*P*=.306) (13).

Pitch Velocity

The first performance metric often viewed when evaluating pitchers is pitching velocity. Matuso et al. (2001) suggested that stabilizing the front leg during SFC helps to transfer force from the lower extremities, through the trunk to the throwing arm (31). Force imparted by the stride leg in the opposite direction of the throw contributes to maximum throwing velocity. Some interpretation may be used to help understand how a more extended stride leg aids increased ball velocity. When comparing the stride leg knee extension angle and velocity of pitchers, Dowling et al. found that the low velocity group (36.1 ± 1.2m/s) had a stride leg extension angle of (5° ± 14°), whereas the high velocity group (40.3 ± 0.9m/s) had a stride leg extension angle of (17° ± 13°). This would indicate that knee extension angle is a predictor of ball velocity (10). However, knee flexion angle has also been shown to have no significance when predicting ball velocity.

Knee angle at SFC showed to have no statistical significance when comparing knee flexion angle at SFC to ball velocity (p =0.704). However, there was statistical significance shown in the comparison of knee flexion angle at maximum external rotation (MER) of the throwing shoulder and stride leg knee flexion angle (p=0.024) (44).

Fleisig et al. evaluated various pitchers from all levels of baseball for kinematic parameters. Kinematic parameters were performed on Youth (n=23), High School (n=33), College (n=115), and Professional (n=60) pitchers in the various phases of the pitching motion. Pitchers threw 10 fastballs at maximum effort. It was found that at front foot contact, knee flexion angles varied, youth (43° ± 12°), high school (50° ± 9°), college (48° ± 12°), and professional (46° ± 8°). At the instance of ball release, knee flexion angle for youth, high school, college, and professional were (36° ± 11°), (43° ± 13°), (39° ± 12°), (38° ± 13°) respectively. Pitch speed was also recorded and was shown to be youth (28 ± 1 m/s), high school (33 ± 2 m/s), college (35 ± 2 m/s), professional (37 ± 2 m/s). No significant differences were found when comparing knee flexion angle in either phase to pitch speed (17). As both Dowling and Fleisig have found evidence of knee flexion angle and velocity to be contradictory, there is still the need to examine knee flexion angle and its influence on pitch velocity.

Pitch Accuracy

Another performance metric often viewed when evaluating pitching performance is pitching accuracy, or the pitcher’s ability to throw the baseball to the targeted pitching zone over home plate. Manzi et al. performed an accuracy study in which pitchers were divided into groups based on the absolute center deviation of each pitcher’s average pitch to the center of the pitching chart by greater or less than 0.5 SD from the mean. A 5 x 5 grid was used to evaluate pitch accuracy, and each square in the grid represented the probability of the pitching group to throw the baseball to that square in the grid. It was reported that when comparing high-accuracy pitchers (14.5% ± 6.7% grid width) and low-accuracy pitchers (33.5% ± 3.7% grid width), the low-accuracy group showed a significantly greater lead knee flexion at maximum throwing shoulder external rotation (46.7 ± 13.5°, *P*=0.028) and ball release (40.1 ± 16.3°, *P*=0.23). High-accuracy pitchers were shown to have significantly less knee flexion at maximum throwing shoulder external rotation (38.9 ± 13.3°) and ball release (30.6 ± 17.8°). Knee flexion angle was referenced as the extension angle of the knee by Dowling et al. (10).

Kung et al. performed a study in which adolescent pitchers completed 6 sets of 15 fastball pitches (90 total), with 5 minutes of rest in between sets. Ball speed, and pitch accuracy were recorded. Pitch accuracy was assessed by a rectangular zone (0.38m wide x 0.64m tall: 0.46m from the ground). A “strike” was a pitch that hit the pitching target within the strike zone. Error or “ball” pitches were divided into 2 sub-groups, “ball 1” or “ball 2”. A ball 1 pitch hit the pitching target, but outside of the strike zone (0.54m margin of error around the strike zone). A ball 2 pitch was a pitch that missed the strike zone completely, known as a “wild pitch”. The second set was the “baseline” set and was considered the pitcher’s peak. Results indicated that as the pitcher increased in pitch count, ball speed decreased significantly in the final set (28.3 ± 2.5 $m \cdot s^{-1}$) compared to the baseline set (29.5 ± 2.5 $m \cdot s^{-1}$). However, there was no significant difference in the percentage of strike (35.5% ± 14.0%), ball 1 (45.1% ± 14.8%), and ball 2 (19.3% ± 10.0%) baseline set when compared to the strike (32.8% ± 10.4%), ball 1 (38.8% ± 15.9%), ball 2 (28.4% ± 11.5%) percentages of the final set (28).

Yanagisawa et al. conducted a study in which 18 baseball pitchers (RH, n=12; LH, n=6) participated in a single game situation. Pitchers threw 13 pitches (9 fastballs and 4 curveballs) from the stretch position at maximal effort. One pitch was thrown every 15 seconds, and pitchers threw for 9 innings with 5 minutes of rest in between innings for a total of 117 pitches. Pitch accuracy was assessed using a passing rate of the strike zone in 9 fastball pitches (number of strikes/9 fastball pitches x100). It was concluded that ball velocity significantly decreased in the 7th (128.4 ± 5.7 km/hr) and 9th innings (127.8 ± 6.8 km/hr) compared to the 1st inning (130.3 ± 6.2 km/hr). Pitch accuracy, however, showed no significant change from the 1st inning throughout each inning until the 9th inning (49).

Injury

Implications that attribute to the increasing number of injuries in baseball include the number of pitches thrown, pitch type, velocity, and pitching mechanics (19). It was reported by Posner et al. that from the 2002 to 2008 baseball seasons, 57% of pitching related injuries occurred at the elbow (26.3%) or the shoulder (30.7%) of the throwing arm (42). Which is why examining the shoulder following a fatigue pitching protocol may be of importance when evaluating pitcher health. Although Maximum ER of the throwing shoulder is vital for throwing velocity, it is also a potential source of injury as the rotator cuff muscles on the back of the shoulder may become pinched in the shoulder joint (16).

Conclusion

Given what we currently know, previous studies and MLB statistics indicate that with increased pitch count, the pitcher begins to fatigue, has more pain and performance will decline (3,32). This is important (MLB) organizations because the costs associated with pitcher throwing related injuries is extreme. According to Spotrac, recorded that 18,369 days were missed by pitchers on the injury list with a throwing-related injury in 2019, which translates into $318,667,058 lost by MLB clubs (45). This amount of time and money lost is an issue that must be addressed. As shown, with increased pitch count, pitcher typically experience more fatigue, have more pain, velocity decreases, shoulder external rotation decreases, and knee flexion angle may be altered. All these effects may impact the health and performance of the pitcher. Therefore, the purpose of this study is to determine how lower extremity fatigue with increased pitch count impacts a pitcher’s joint kinematics, muscle activation levels, and pitching performance so that coaches may better be able to decide when to take a pitcher out of a game. Thus, during a simulated baseball pitching session, in which the pitcher experiences lower extremity muscle fatigue, the pitchers throwing shoulder and stride leg knee joint kinematics will be examined during each pitching phase, along with lower extremity muscle activation levels in each pitching phase as well as pitch velocity and accuracy measures.

Chapter 3 – Methods

Participants

Eleven high school and collegiate baseball pitchers (age: 16.67 ± 0.86 years, height: 1.78 ± 0.08 m, weight: 74.6 ± 14.82 kg) with 11.4 ± 1.59 years of experience, participated in this study. Two participants data were excluded from the study due to technical errors with the Noraxon equipment. Participants level of physical conditioning was not assessed, but participants were in appropriate physical conditioning to throw until they were physically fatigued. Inclusion criteria required participants be actively pitching in season. Pitchers were required to be 16-22 years old, healthy, not have had any surgeries within the past 12 months and be without any physical limitations that may increase the risk of injury during the pitching session. The participant had to able to throw a minimum of 60 pitches. The East Carolina University Institutional Review Board approved the investigation, and each participant was informed of the experimental risks and provided written informed consent before testing.

Measurements

Muscle activation levels and kinematics were measured using the 16-channel Noraxon ultium portable lab (Noraxon Inc, Scottsdale, AZ, USA). Eight 20 mm disposable Ag/AgCl surface EMG electrodes (Noraxon, Scottsdale, Arizona, USA) were used for data collection. The 8-channel ultium EMG (Noraxon Inc, Scottsdale, AZ, USA) was used to record muscle activation levels at a sampling rate of 2000 Hz. The Noraxon Ultium had a lowpass filter to remove any EMG drift set to 500 Hz. An EMG highpass filter was set to 10 Hz to remove motion artifacts. Electrode impedances were between 0-25 MΩ to ensure proper electrical signal measurement. The EMG signal was sent to the Noraxon portable lab receiver/amplifier and then passed through to a Dell laptop. Ultium motion sensors (Noraxon Inc, Scottsdale, AZ, USA) captured 3D kinematics at a sampling rate of 200 Hz. The Ninox 120 video camera (Noraxon Inc, Scottsdale, AZ, USA) was used to capture real-time video, collected at 1920X1080 resolution at 60 Hz to determine each of the six pitching phases of the pitching motion. Noraxon MyoReseach XP (Noraxon Inc, Scottsdale, AZ, USA) software was used for all data collection and reduction. Pitches were performed on an artificial pitching mound with participants throwing toward a 3x3 target strike zone located 18.4 m from the pitching rubber. Ball velocities were recorded using a radar gun (Stalker Sport 2 Radar Gun, Richardson, Texas, USA).

Procedures

Participants were given an explanation as to how the study was going to be performed and they signed informed consent and assent forms, parents signed the parental form approving of their child to participate if they were under the age of 18. Participants were given a demographics survey (Appendix I) about all past baseball pitching experience. Participants height (m) and weight (kg) were measured prior to placement of EMG electrodes and sensors along with IMU sensors. Ten free-response questions were asked, such as height, weight, age, years of experience playing baseball, what arm they throw with, and highest level of competition. Two fill in the bubble questions were asked, such as gender, and starting position of throwing, i.e., stretch or windup.

After each inning pitched, participants gave a self-estimate of their fatigue by reporting their RPE (Appendix II). The Borg’s scale from 0-10 was used, 0: No exertion, at rest, 1: Very light, 2-3: Light, 4-5: Moderate, somewhat hard, 6-7: High, vigorous, 8-9: Very hard, 10:

Maximum effort, highest possible. If the participant were to self-report an RPE of 10, the study was to be stopped so there is no increased risk of injury.

EMG Electrode Placement

After completing demographics and informed consent, each participant completed their own 10-minute full body warm up routine. After their warmup, participants had their lower extremities shaved, debrided, and cleaned with alcohol pads in preparation for EMG electrodes and sensor application (Noraxon Inc, Scottsdale, AZ, USA). Prior to data collection, locations for EMG electrode placement were determined, as shown in Figure 1. On the stride leg of the pitcher, Noraxon surface electrodes (Noraxon Inc, Scottsdale, AZ, USA) were placed on 2 superficial muscles of the quadriceps (Vastus lateralis (VL) muscle and Vastus Medialis (VM) muscle). Electrodes were also placed on the gastrocnemius (GAST), biceps femoris (BF), and semitendinosus (SEMI) muscles of the stride leg. On the drive leg of the pitcher, electrodes were placed on the gluteus maximus (GM), vastus lateralis (VL), and vastus medialis (VM) muscles. In accordance with SENIAM recommendations for electrode location on the human body, the GAST electrode was placed on the most prominent bulge of the muscle parallel to the muscle fibers. Electrodes on the VL were placed four finger widths above the patella. The VM electrodes were placed in the middle of the inferior portion of the muscle belly. The BF electrode was placed on the muscle belly of the lateral side of the hamstring, found by following the biceps femoris tendon to the muscle belly. The SEMI electrode was placed on the muscle belly on the medial side of the hamstring, found by following the SEMI tendon to the muscle belly. The GM electrode was placed on the muscle belly of the GM just lateral to the sacrum. All EMG sensors were placed parallel to the electrodes and away from the muscle belly of each muscle in question.

Figure 1: EMG electrodes and sensors were placed in pre-determined locations. This was a right-handed thrower, therefore electrodes on the muscle belly of the Vastus Lateralis (VM), Vastus Medialis (VM), Biceps Femoris (BF), Semitendinosus (SEMI), and Medial Gastrocnemius (GAST) muscles of the stride leg (left leg). Electrodes were placed on the muscle belly of the Vastus Lateralis (VM), and Vastus Medialis (VM) muscles of the drive leg (right leg).

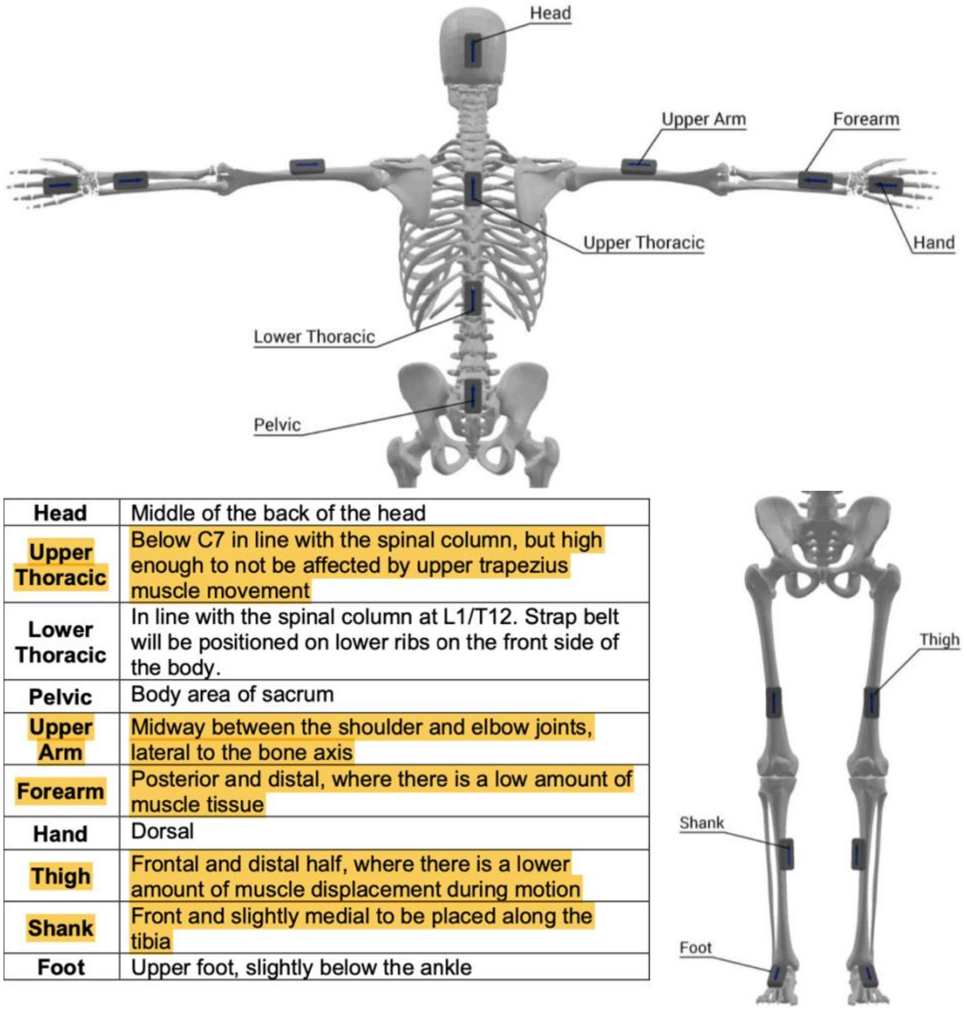
MVIC

A maximal voluntary isometric contraction (MVIC) was recorded to give a baseline of muscle activation levels for the muscles in question. Participants performed each MVIC for 5 seconds and twice for each movement. To determine the MVIC of the VL and VM, participants sat on an athletic training table and performed a leg extension that was met with manual resistance. For the GAST MVIC, the tester stood elevated above the participant’s shoulders, the participant performed the peak concentric phase of plantar flexion. The tester then manually pressed down on the participant's shoulders. For both the BF and SEMI, participants laid prone on the table and flexed their knee to 90-degrees, the tester then manually pulled the shank into knee extension as the participant resisted extension. For the GM, the participant laid prone on the table with the leg at 90-degrees of flexion, with one hand the tester pressed on the hips to stop them from lifting off the table and with the other the tester pressed on the hamstring distal to the gluteus maximus manually with maximal resistance.

Inertial Measurement Unit placement

Placement of IMU's was pre-determined based on Noraxon Utlium MyoMotion software (Noraxon Inc, Scottsdale, AZ, USA), as seen in Figure 2. To measure knee flexion angle, as shown in the software of Noraxon MyoResearch (Noraxon Inc, Scottsdale, AZ, USA), the shank IMU was placed on the anterior side of the stride leg tibia halfway between the patella and the talus of the ankle. Another IMU was placed on the lateral side of the stride leg thigh halfway between patella and greater trochanter along the iliotibial band.

To collect throwing shoulder external rotation data, IMU sensors were placed on three pre-determined locations of the upper body. An IMU sensor was placed on the upper thoracic region of the trunk in line with C7/L1, but high enough not to be affected by the trapezius muscles. An IMU sensor was placed on the upper arm of the throwing shoulder midway between the proximal and distal ends of the humerus. The last IMU sensor was placed on the posterior distal region of the throwing arm forearm where there is minimal muscle tissue. After participants had all electrodes and sensors correctly and securely placed, participants were asked to stand in an upright position to calibrate all EMG and IMU sensors in preparation for data collection.



Head	Middle of the back of the head
Upper Thoracic	Below C7 in line with the spinal column, but high enough to not be affected by upper trapezius muscle movement
Lower Thoracic	In line with the spinal column at L1/T12. Strap belt will be positioned on lower ribs on the front side of the body.
Pelvic	Body area of sacrum
Upper Arm	Midway between the shoulder and elbow joints, lateral to the bone axis
Forearm	Posterior and distal, where there is a low amount of muscle tissue
Hand	Dorsal
Thigh	Frontal and distal half, where there is a lower amount of muscle displacement during motion
Shank	Front and slightly medial to be placed along the tibia
Foot	Upper foot, slightly below the ankle

Figure 2: Location of IMU's were pre-determined based on Noraxon Utlium MyoMotion software (Noraxon Inc, Scottsdale, AZ, USA). IMU's will be placed on the upper thoracic spine, upper arm, as well as forearm of throwing arm, along with thigh, and shank of stride leg.

After all electrodes and sensors were placed and calibrated participants performed another 10-minute warmup if needed to get acclimated to moving and throwing with the electrodes and sensors on.

After each inning pitched, all electrodes and sensors were inspected to ensure proper skin adherence and secureness. Pitch type thrown in each inning was randomized before each pitcher begins the pitching session. Pitchers threw 14-20 pitches per inning and the amount per inning was randomized as well, each pitcher threw a minimum of 60 pitches and no more than 105 pitches total. At the end of each inning, Borg’s 0-10 RPE scale was used to determine the pitchers rating of perceived exertion, if the participant self-reported an RPE of 10, the study was stopped. In between innings, pitchers were given a total of 5 minutes of rest and then 5 warm up pitches before the next inning if they chose.

When evaluating accuracy and effort, a 3x3 target strike zone was placed directly over home plate 18.4 m away from the pitching rubber. Each pitch in each inning was recorded as a strike if it hit the 3x3 target strike zone on a fly or a ball if the baseball failed to hit the target strike zone or hit the target strike zone on a bounce.

Data Reduction

All IMU data was rectified and then smoothed using a 100-millisecond root mean square method. EMG data was processed using a custom Matlab script.

Data analysis

Once IMU data was reduced and smoothed, data analysis was performed by first exporting all data collected via the Noraxon Utlium portable lab (Noraxon Inc, Scottsdale, AZ, USA) to Excel as .slk files. The .slk files were then re-saved as .xls files to be processed in Matlab_R2023a, with the assistance of ChatGPT. As six phases of the pitching motion were chosen to be examined, marker names were placed in the Noraxon files and exported into the Excel files with all data. Matlab_R2023a scripts were created to process data by separating each of the phases of the pitching motion and calculate the mean and standard deviation of all IMU data for knee flexion angle and shoulder external rotation at each end point of each phase for the first and last innings pitched.

To process EMG data, unprocessed data from the first and last innings was exported to Excel as a .slk file and then re-saved as a .xls file to use Matlab_R2023a to process the data. Power spectral density and median frequency of EMG data from the first and last inning were calculated using a custom Matlab_R2023a script to determine muscle fatigue. In the Matlab script, sampling rate was set to 2000 Hz with a low bandpass filter set to 10 Hz and a high bandpass filter set to 500 Hz. A power spectrum was then plotted with median frequency being calculated.

Pitch accuracy and velocity were recorded with mean and standard deviation calculated in Excel for fastball, off-speed, and breaking ball.

Mean and standard deviation were calculated for pitch velocity, and pitch accuracy, along with EMG, throwing shoulder external rotation, and knee flexion angle during each of the 6 phases of the pitching motion for the first and last innings. Differences between the first and last inning were analyzed using a repeated measures ANOVA and Cohen's d for effect size for median frequency of EMG, pitch velocity of fastball, off-speed, and breaking ball, pitch accuracy, stride leg knee flexion angle, and throwing shoulder external rotation. The significance level was set at $P < .05$. Repeated measures ANOVA were calculated using SPSS 29.0.1.0. A Cohen's d was calculated in Excel for all data to determine effect size.

Chapter 4 – Results

The purpose of this study was to determine how lower extremity fatigue with increased pitch count impacts a pitcher's joint kinematics, muscle activation levels, and pitching performance so that coaches may better be able decide when to take a pitcher out of a game. It was hypothesized that with increased pitch count, there will be a decrease in the EMG median frequency values, there will be a decrease in throwing shoulder external rotation, stride leg knee flexion angle will increase, pitched pitcher throwing velocity will decrease, and changes will be seen in accuracy. For each analysis, a within subjects repeated measures ANOVA for the first and last inning recorded was performed. A Cohen's d for effect size was also calculated for each variable for the first and last inning.

Median Frequency

There were no significant differences between the average median frequency for any of the muscles investigated for all participants from the first to last inning pitched. There was a moderate Cohen's d effect size for the right vastus medialis (*d*=0.474) and left vastus medialis (*d*=0.444).

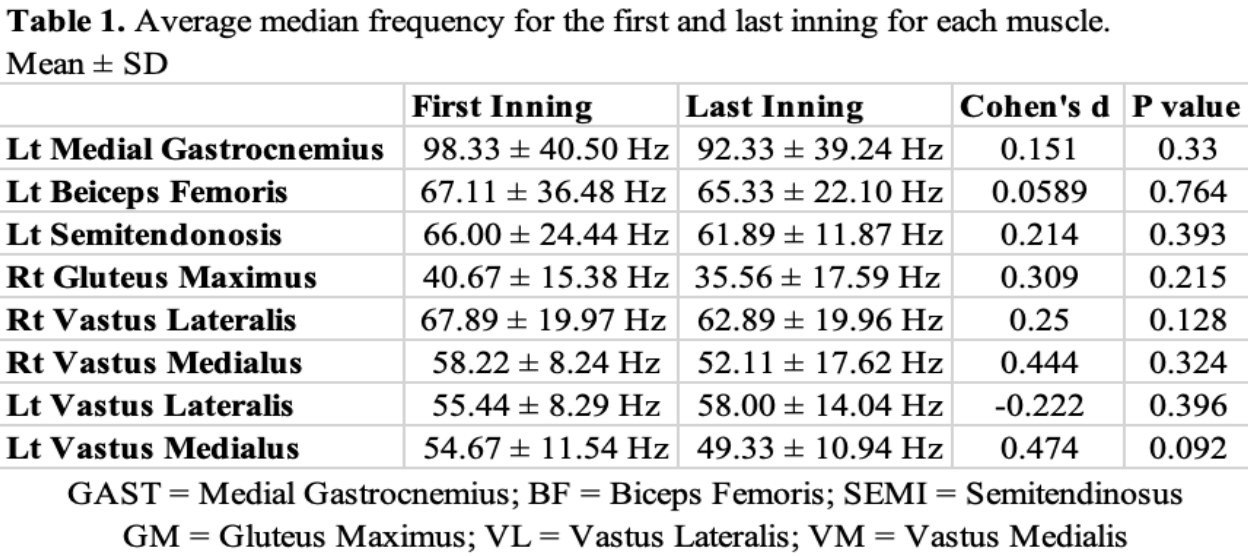


Table 1. Average median frequency for the first and last inning for each muscle.
Mean ± SD

	First Inning	Last Inning	Cohen's d	P value
Lt Medial Gastrocnemius	98.33 ± 40.50 Hz	92.33 ± 39.24 Hz	0.151	0.33
Lt Beiceps Femoris	67.11 ± 36.48 Hz	65.33 ± 22.10 Hz	0.0589	0.764
Lt Semitendonosis	66.00 ± 24.44 Hz	61.89 ± 11.87 Hz	0.214	0.393
Rt Gluteus Maximus	40.67 ± 15.38 Hz	35.56 ± 17.59 Hz	0.309	0.215
Rt Vastus Lateralis	67.89 ± 19.97 Hz	62.89 ± 19.96 Hz	0.25	0.128
Rt Vastus Medialus	58.22 ± 8.24 Hz	52.11 ± 17.62 Hz	0.444	0.324
Lt Vastus Lateralis	55.44 ± 8.29 Hz	58.00 ± 14.04 Hz	-0.222	0.396
Lt Vastus Medialus	54.67 ± 11.54 Hz	49.33 ± 10.94 Hz	0.474	0.092

GAST = Medial Gastrocnemius; BF = Biceps Femoris; SEMI = Semitendinosus
GM = Gluteus Maximus; VL = Vastus Lateralis; VM = Vastus Medialis

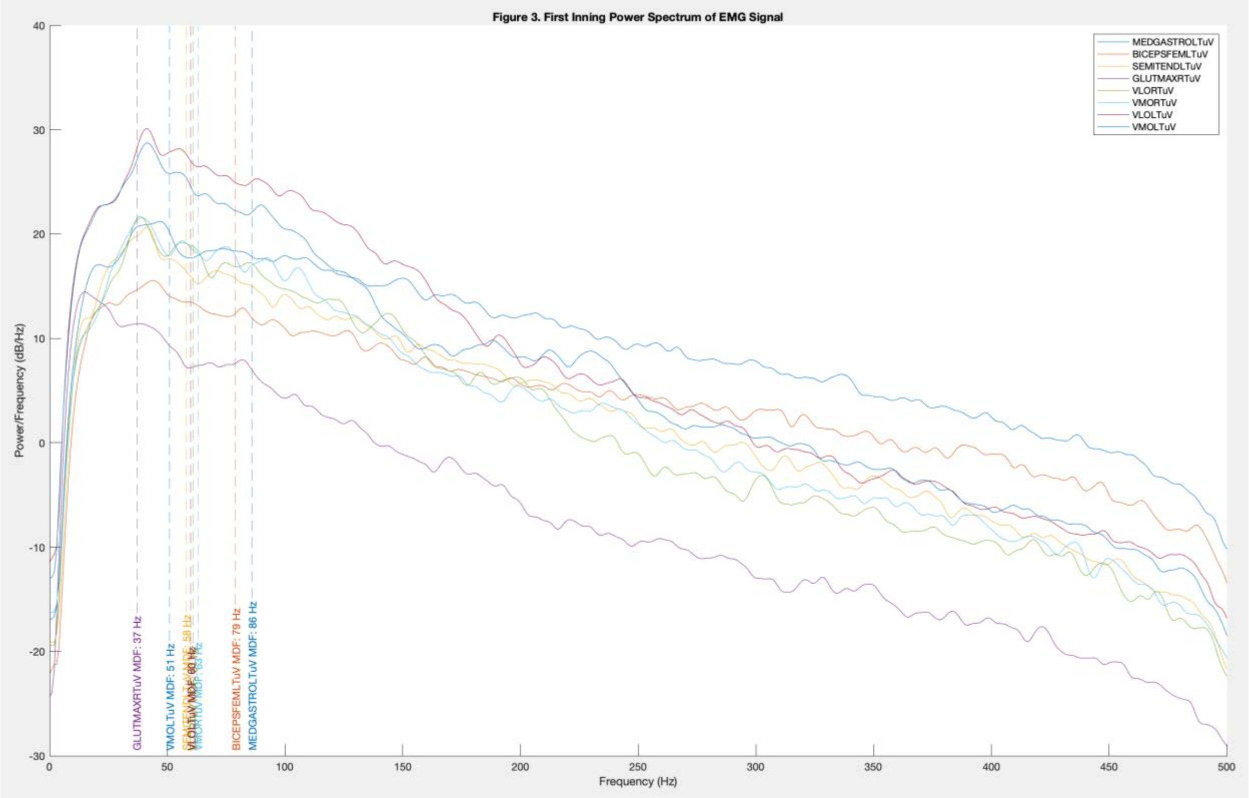


Figure 3. First Inning Power Spectrum of EMG Signal

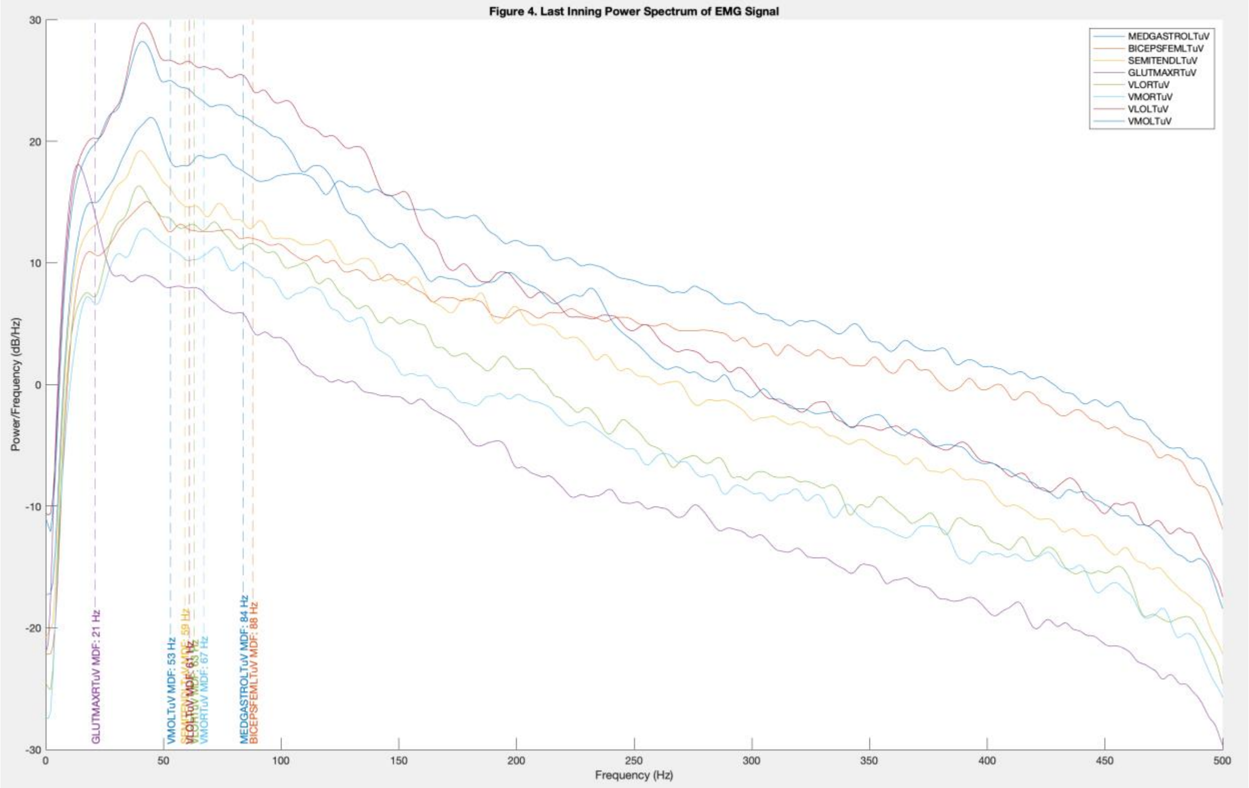


Figure 4. Last Inning Power Spectrum of EMG Signal

Shoulder External Rotation Joint Kinematic

There was significance found in the throwing shoulder external rotation degree from first to last inning in the follow through phase (*p*=0.03) as shown in Table 2. A moderate Cohen's d effect size for the throwing shoulder external rotation for the Wind-up phase (*d*=0.436) and SFC phase (*d*=0.515) was seen.

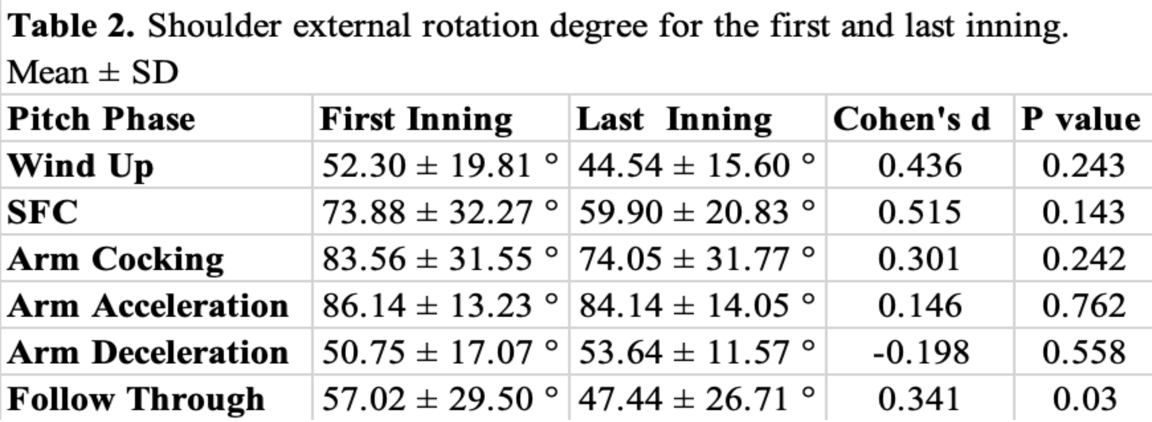


Table 2. Shoulder external rotation degree for the first and last inning. Mean ± SD

Pitch Phase	**First Inning**	**Last Inning**	**Cohen's d**	**P value**
Wind Up	52.30 ± 19.81 °	44.54 ± 15.60 °	0.436	0.243
SFC	73.88 ± 32.27 °	59.90 ± 20.83 °	0.515	0.143
Arm Cocking	83.56 ± 31.55 °	74.05 ± 31.77 °	0.301	0.242
Arm Acceleration	86.14 ± 13.23 °	84.14 ± 14.05 °	0.146	0.762
Arm Deceleration	50.75 ± 17.07 °	53.64 ± 11.57 °	-0.198	0.558
Follow Through	57.02 ± 29.50 °	47.44 ± 26.71 °	0.341	0.03

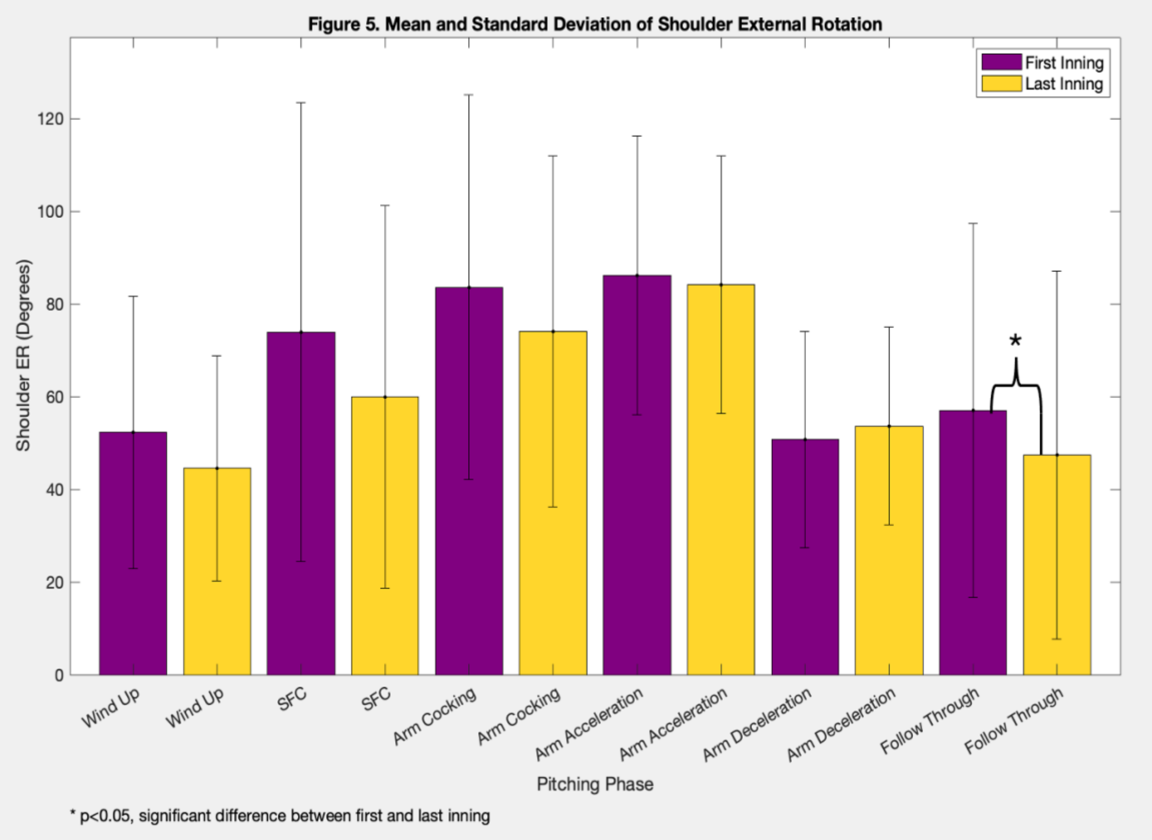


Figure 5. Mean and Standard Deviation of Shoulder External Rotation

* p<0.05, significant difference between first and last inning

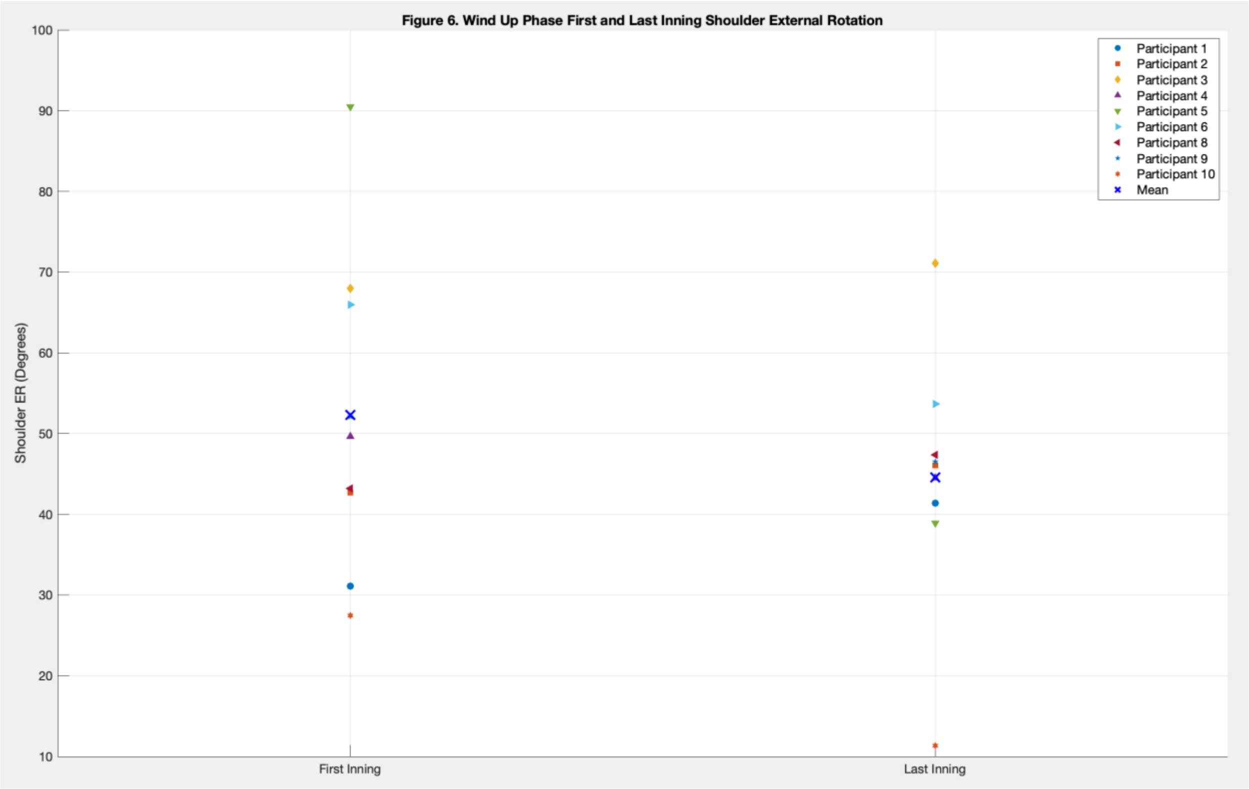


Figure 6. Wind Up Phase First and Last Inning Shoulder External Rotation

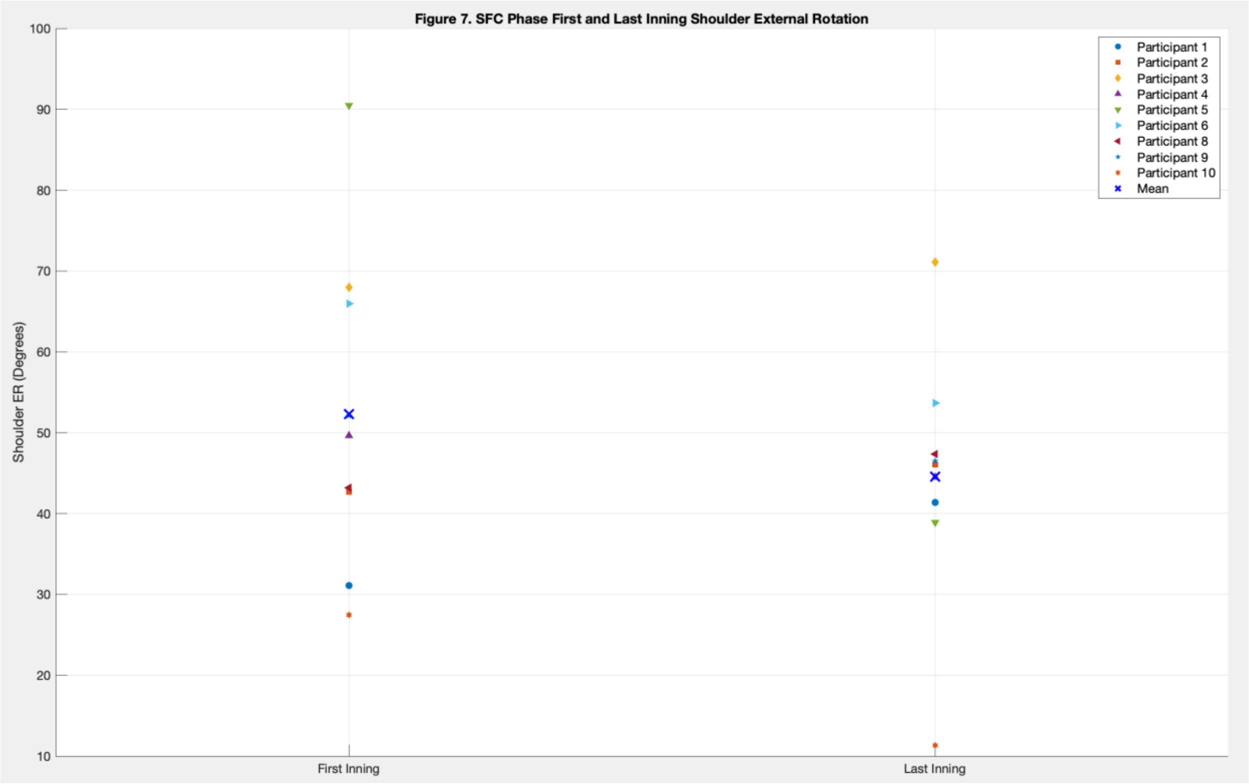


Figure 7. SFC Phase First and Last Inning Shoulder External Rotation

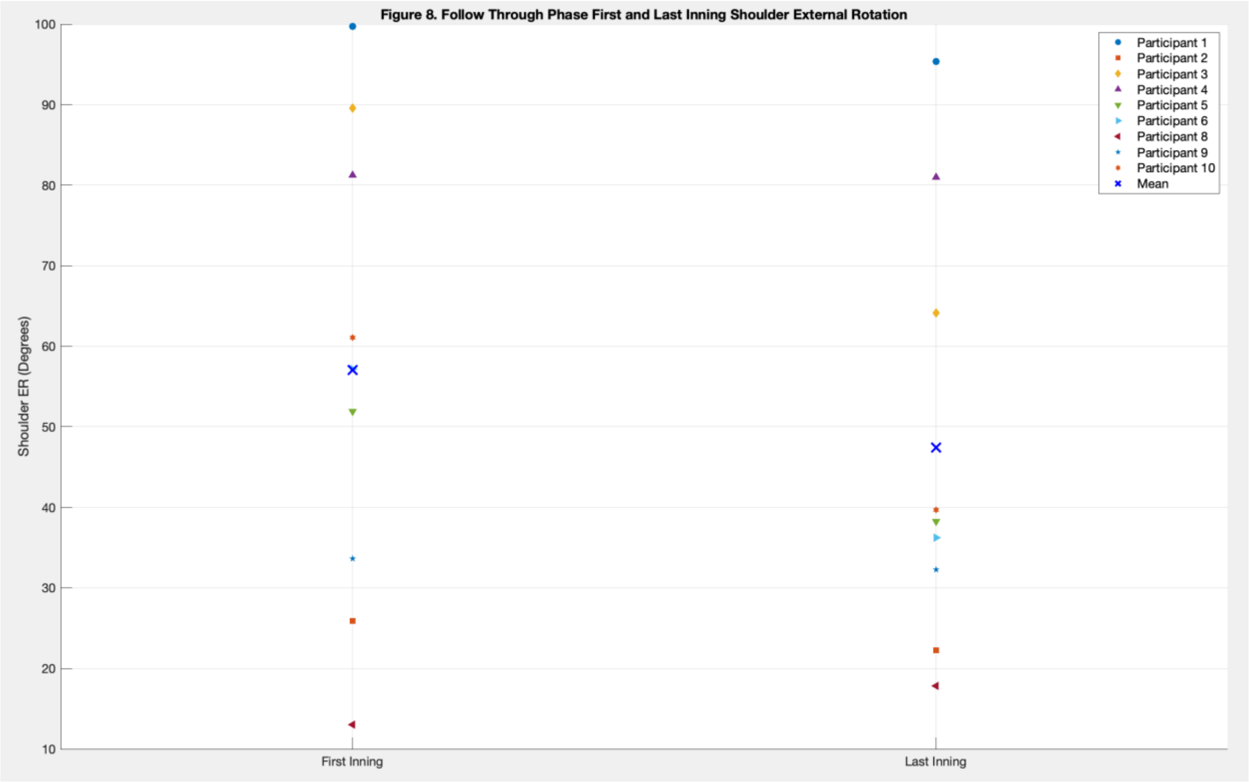


Figure 8. Follow Through Phase First and Last Inning Shoulder External Rotation

Knee Flexion Angle Joint Kinematic

There were no significant differences found in knee flexion angle degree from the first to last inning pitched.

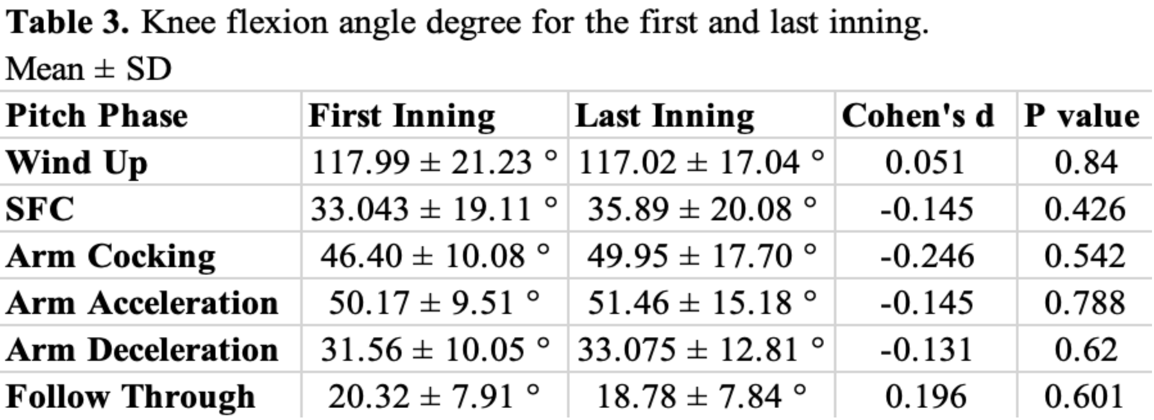


Table 3. Knee flexion angle degree for the first and last inning.

Mean ± SD

Pitch Phase	First Inning	Last Inning	Cohen's d	P value
Wind Up	117.99 ± 21.23 °	117.02 ± 17.04 °	0.051	0.84
SFC	33.043 ± 19.11 °	35.89 ± 20.08 °	-0.145	0.426
Arm Cocking	46.40 ± 10.08 °	49.95 ± 17.70 °	-0.246	0.542
Arm Acceleration	50.17 ± 9.51 °	51.46 ± 15.18 °	-0.145	0.788
Arm Deceleration	31.56 ± 10.05 °	33.075 ± 12.81 °	-0.131	0.62
Follow Through	20.32 ± 7.91 °	18.78 ± 7.84 °	0.196	0.601

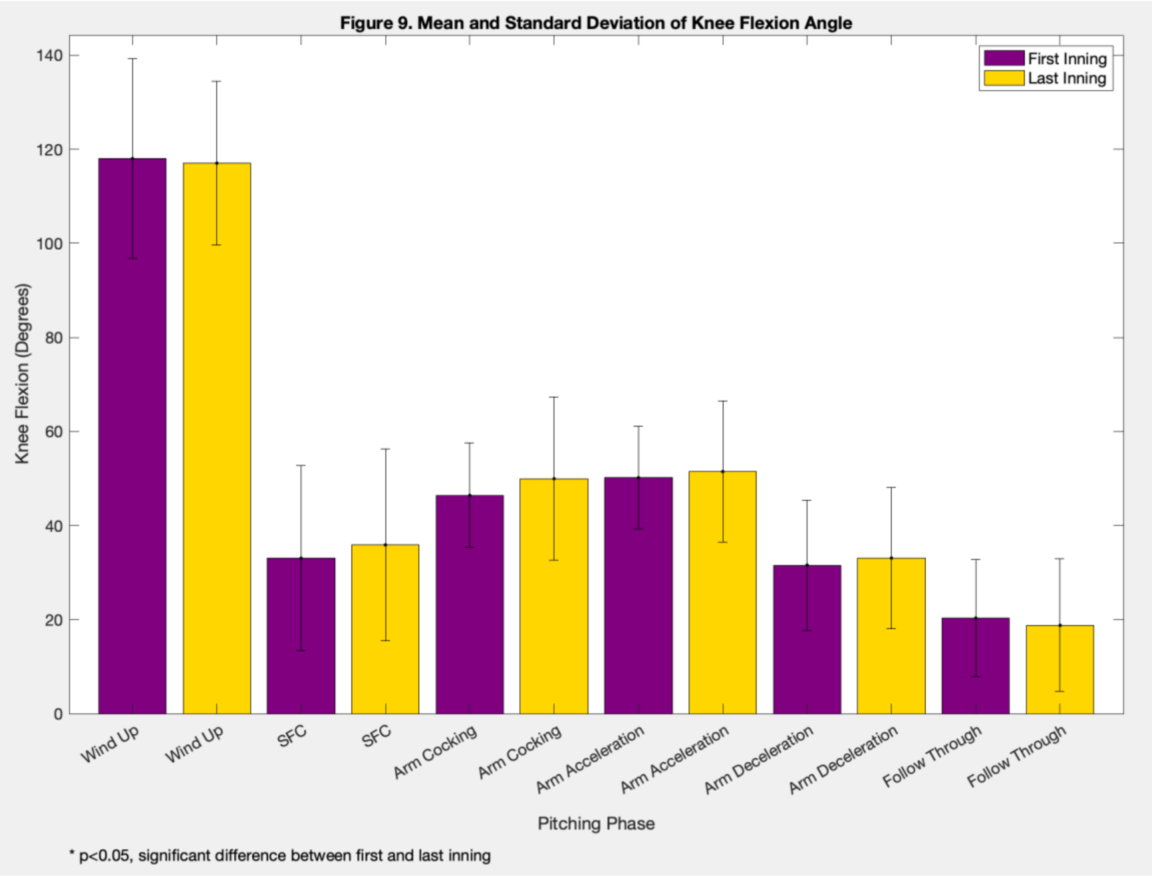


Figure 9. Mean and Standard Deviation of Knee Flexion Angle

* p<0.05, significant difference between first and last inning

Pitch Velocity

Pitch velocity for fastball, offspeed, and breakingball were largely unchanged and thus no significant difference from the first to last inning were found.

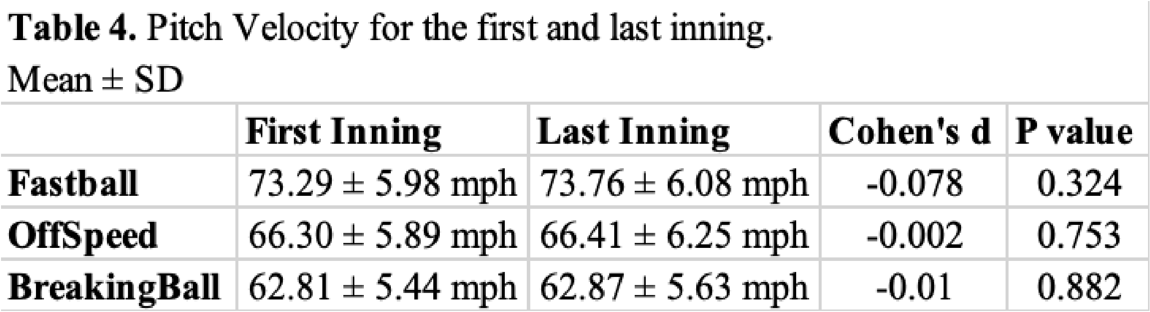


Table 4. Pitch Velocity for the first and last inning.
Mean ± SD

	First Inning	Last Inning	Cohen's d	P value
Fastball	73.29 ± 5.98 mph	73.76 ± 6.08 mph	-0.078	0.324
OffSpeed	66.30 ± 5.89 mph	66.41 ± 6.25 mph	-0.002	0.753
BreakingBall	62.81 ± 5.44 mph	62.87 ± 5.63 mph	-0.01	0.882

Pitch Accuracy

Pitch accuracy for fastball, offspeed, and breakingball was found to decrease from the first to last inning, however there was no significance. A moderate Cohen's d effect size for pitch accuracy of the breakingball from first to last inning (*d*=0.63) was seen.

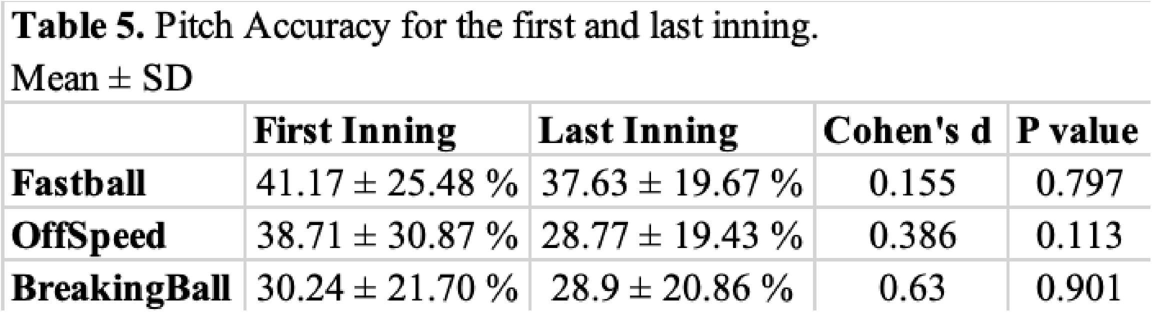


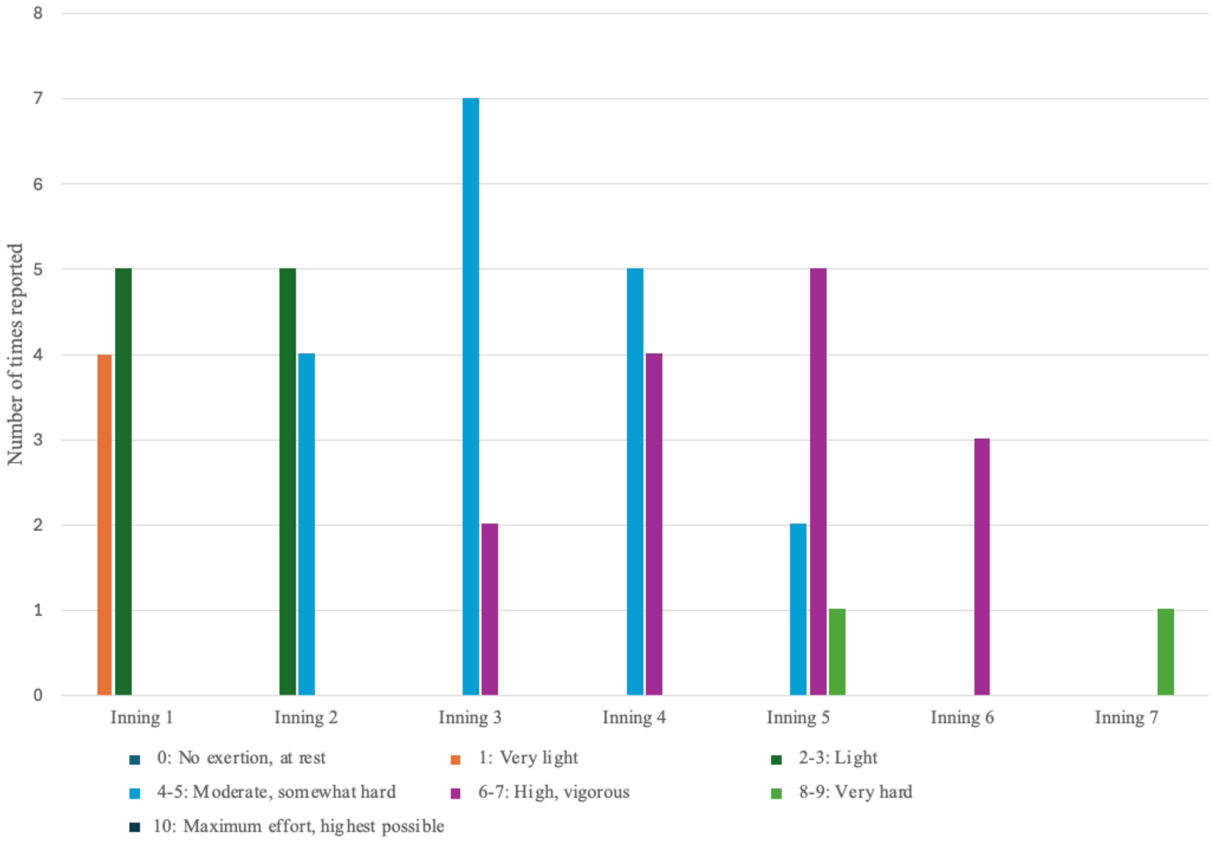
Table 5. Pitch Accuracy for the first and last inning.
Mean ± SD

	First Inning	Last Inning	Cohen's d	P value
Fastball	41.17 ± 25.48 %	37.63 ± 19.67 %	0.155	0.797
OffSpeed	38.71 ± 30.87 %	28.77 ± 19.43 %	0.386	0.113
BreakingBall	30.24 ± 21.70 %	28.9 ± 20.86 %	0.63	0.901

Rate of Perceived Exertion

No statistics were calculated for RPE as it was mainly utilized to be a real-time objective measure to determine if the participants were still fit to participate in the study. If a participate were to reach a 10 on the scale the study would stop. Figure 7 gives a visualization of the RPE data collected to show that in fact the participants did continually feel as if they were fatiguing.

Figure 10. Rate of Pereived Exertion reported by each participant



Chapter 5 – Discussion

The purpose of this study was to determine how lower extremity fatigue with increased pitch count impacts a pitcher’s joint kinematics, muscle activation levels, and pitching performance so that coaches may better be able to decide when to take a pitcher out of a game. It was hypothesized that with increased pitch count, a decrease in the EMG median frequency values, a decrease in throwing shoulder external rotation, stride leg knee flexion angle will increase, pitched pitcher throwing velocity will decrease, and changes will be seen in accuracy.

The only hypothesis supported was that there was a significant decrease of shoulder external rotation degree in the follow through phase from the first to last inning (p=0.03).

Median Frequency

Main findings suggest there was no significant difference in median frequency from first to last inning (p<0.05). However, in Table 1, it can be seen from first to last inning in seven out of the eight lower extremity muscle there was still a decrease in the median frequency (Hz) by about 3-5 Hz. In Figure 7, although every participant did not complete the same number of innings or throw the same number of pitches, the RPE scale did aid in displaying the increase in RPE from inning-to-inning. Figure 7 shows that with each progressing inning, there were participants that continued to increase in RPE and as expected all participants did end the study with reporting a higher RPE than when they began the study. This shows that although there was no significant decrease in median frequency, it may still be concluded that regarding mean differences in first to last inning median frequency and RPE, there was still some fatiguing that occurred in participants.

When examining the median frequency, standard deviation values being upwards of 20-40 Hz for the RT VL, SEMI, BF, and GAST do not correspond with the literature surrounding muscle fatigue and dynamic movements (2,34). This may indicate that there were varying levels of physical conditioning among the participants or varying degrees to which the participants were able to recruit motor units of those muscles. More specifically when looking at the standard deviation in the hamstring and quadriceps muscles from first to last inning, we see what seems to be an inverse relationship in median frequency. It seems as if in the biceps femoris and semitendinosus muscles there is less variability in the last inning when it is believed there is fatiguing that occurs. Whereas more variability was seen in the quadriceps muscles which may again suggest varying levels of physical conditioning or muscular compensation in which the quadriceps begin to be utilized more with increased pitch counts.

When examining previous research (41), three MVC tests were performed for the quadriceps muscles reporting VM (T1 104.36 ± 22.05 Hz, T2 105.48 ± 20.04 Hz, T3 107.15 ± 22.06 Hz), VL (T1 157.88 ± 23.21 Hz, T2 158.07 ± 23.16 Hz, T3 157.83 ± 25.24 Hz), and RF (T1 120.95 ± 20.49 Hz, T2 119.06 ± 19.79 Hz, T3 120.57 ± 19.31 Hz) median frequencies to be much larger than those recorded in this study. This may be because there are differences in the median frequency between the type of muscular contraction performed (11). Enoka et al note that the magnitude of decline in voluntary activation during fatiguing ranges from minimal to substantial. When comparing maximal shortening and isometric, MVC voluntary activation decreased greater in the isometric contraction (35.7 ± 3.8%) compared to the shortening contraction (26.5 ± 2.1%) (11). However, individual motivation must always be considered to report accurate levels of muscle activation.

Shoulder External Rotation Joint Kinematic

Previous research has stated that with increased pitch count, maximum shoulder external rotation decreases and knee flexion angle increases (35), which may negatively influence the pitcher's ball velocity (4). As shown in Table 2, a significant decrease in shoulder external rotation during the follow-through phase of the pitching motion was seen. It is unclear why the shoulder external rotation degree in the follow through phase was found to be significant as it has not been shown to provide any benefit to pitching performance or shoulder health as the follow through phase is when the pitcher has thrown the ball and is typically in a fielding position. Our values are comparable to Fleisig et al regarding shoulder external rotation in the SFC phase as Fleisig et al reported shoulder external rotation degrees for High school (64°±25°) and College pitchers (55°±29°) to also not be significant. We also found similar variations in standard deviation when compared to Escamilla et al, however Escamilla et al do not report a decrease in shoulder external rotation from first to last inning of the SFC phase. This may indicate that in the SFC phase there is much variability as to an increase or decrease of mean shoulder external rotation, along with variation within participants and their shoulder range of motion.

An about nine degrees difference of shoulder external rotation from the first to last inning in the arm cocking phase was seen in our study, however our mean and standard deviation (83.56° ± 31.55°, 74.05° ± 31.77°) are much different when compared to Escamilla et al (175° ± 10°, 173° ± 10°). It should also be noted that compared to previous research (13,15,35), we have reported about 50° to 90° differences in shoulder external rotation means. Previous studies (13,15,35) did utilize Motion Capture to record shoulder external rotation data in their pitchers. Camp et al ultimately concluded that wearable motusBASEBALL IMU sensor was not accurate or valid for shoulder rotation compared to marker-based motion capture. The motusBASEBALL IMU does appear to be similar in its recording capabilities to the Noraxon IMU used in this study. Regarding the data recorded, although there is nothing noted in Noraxon documentation regarding the IMU's processing of data, there is a possibility of an offset. This is possible as before rectifying or smoothing the IMU data in Noraxon, the data is presented in the positive, as well as the negative by about the 50° to 90° difference. Then once the rectification and smoothing are performed in Noraxon, all data was in the positive, suggesting an offset to be the possible reason for the difference in mean values with previous research (13,15,35).

Camp et al, state that with an increase in shoulder external rotation, there is an increased risk of elbow injury due to the high demands placed on the upper extremity during overhead throwing. Although, the results were non-significant, the effect size for the Wind Up (d=0.436) and SFC (d=0.515) phase were moderate and indicates that there was a large difference in the shoulder external rotation mean from the first to last inning. In the Wind-Up phase there was an 8° difference from first to last inning and in the SFC phase there was an about 14° difference from first to last inning. Previous research has shown that this difference from first to last inning is consistent as Murray et al reported a 9° decrease in shoulder external rotation from 181° to 172° respectively. Escamilla et al also reported a decrease in shoulder external rotation from the first inning (175 ± 10) to last inning (173 ± 10), with a small effect size of 0.2. Overall, it is unclear as to why there is a decrease in shoulder external rotation with increased pitch count, it may occur naturally to protect the shoulder, or there may have shoulder fatiguing that we could not account for in this study other than the self-reported RPE.

Knee Flexion Angle Joint Kinematic

Previous research has stated some varying results pertaining to stride leg knee flexion angle being both increased and decreased with increased pitch count (10, 13, 23, 35), it was found that knee flexion angle was not significantly different from the first to last inning in any pitch phase.

In the Arm Cocking phase as shown in Table 3, there was an increase in knee flexion angle from first to last inning (46.40° ± 10.08°, 49.95° ± 17.70°), although there was no significance (*p*=0.542) an increase in standard deviation from first to last inning indicating that there was more variability of knee flexion angle in the last inning was seen.

Erikson et al have reported that knee flexion angle increased from first to last inning (49° ± 15°, 53° ± 15° *p*=0.08) at ball release with a negative small effect size, which does correspond to our results. Murray et al reported that in reference to lead knee extension angle there was an 8° decrease in knee extension (*p*=0.024) which correlates to an increase in knee flexion. Escamilla et al reported no change in knee flexion angle from the first inning (47 ± 11°) to the last inning (47 ± 12°), with a small effect size (d=0). Although both studies found an increase in knee flexion angle at ball release, neither saw a significant difference. Overall, it is noteworthy that there was a slight increase in knee flexion angle from first to last inning, however, not see as much of an increase as previous research (10, 13, 23, 35), suggests.

Pitch Velocity

Pitchers averaged 80 ± 13 pitches over the course of the study, which is lower than the pitch count of previous studies (8,14,28). There was no significant change in pitch velocity for fastball, offspeed, and breakingball which was not expected, as previous research indicates pitch velocity to decrease with increased pitch count (8,14,28). Previous studies (27, 49) have all reported similar values for pitch velocities as reported in Table 4. There was an about 2-3 mph greater difference in standard deviation compared to those studies, suggesting we may have recruited a more diverse population with varying skill level that were not as similar in pitch velocity as previous studies.

Pitch Accuracy

There was no significant difference in pitch accuracy, which aligns with previous research stating that pitch accuracy is typically unchanged with increased pitch count (21,38). A moderate effect size for breakingball pitch accuracy from first to last inning (d=0.63) was seen, which would suggest that there was a moderate mean difference for breakingball from first to last inning. Pitch accuracy is an important aspect to baseball pitching and has been well researched. As seen in Table 5, we have gathered pitch accuracy data similar to those previous researched (27, 49). It can be concluded that pitch accuracy does not change over the course of a pitching outing or simulation.

Strengths and Limitations

A main strength of this was investigating lower extremity muscular fatigue along with joint kinematics of the throwing shoulder and stride leg knee of the pitcher with pitch velocity and accuracy. These variables combined have not been looked at together in one study. The RPE scale as reported in Figure 5., also well represented the self-reporting of participants perceived overall body exertion as most participants reported their last inning pitched as being high, vigorous or very hard with one participant saying their last inning was moderately to somewhat hard.

There were limitations associated with this study. The main limitation was sample size, this led to high standard deviations with median frequency, shoulder external rotation, and knee flexion angles. The small sample size may have also led to this study being under powered. It is our belief that with more participants, there would be more conclusive evidence regarding the increase in pitch count and fatigue, joint kinematics, and pitching performance outcomes. Another limitation is the population recruited, both high school and collegiate pitchers were recruited, however we did not have enough data to compare between the groups or recruit from just one group as previous studies have done (15,18,21). All joint kinematics were recorded via Noraxon IMU's, which previous research has not particularly performed (13,15,35). Previously (13,15,35), shoulder external rotation and knee flexion angle have been recorded marker-based motion capture systems which appear to be more accurate at capturing joint kinematics in a baseball setting.

Another limitation would include not recording when participants last pitched in either practice or a game, which would give us potentially another measure of their physical fitness and readiness to participate in this study. Finally, it should be noted that this was a simulated pitching outing in which the pitcher did not face an opponent and pitched in doors. This may have an impact on pitcher motivation, which is also very hard to measure.

Takeaways

There were limitations that may have impacted the outcomes of this study, such as an indoor setting, no batter for the pitcher to face, the sample size recruited does not seem to be enough, the use of IMU's may not be reliable when compared to other measures, and physical fitness of the participants. Throughout literature and shown in this study, there is no range or defined pitch count that equates to lower extremity fatigue. It also came into question if participant motivation was accurately represented and if motivation or lack thereof was the cause for a lack of change in pitch velocity and accuracy. We did however find a decrease in median frequency from first to last inning for seven out of the eight muscles investigated. Along with RPE scores, we may be able to conclude there was some fatiguing that occurred. More specifically there were large decreases in shoulder external rotation from first to last inning for the Wind Up, SFC, Arm Cocking, and Follow Through phases, which may need more investigating as to why this occurs.

Future Directions

Although participants were unable to reach a significant difference in median frequency for all lower extremity muscle from first to last inning, future research is still needed to investigate the impacts of increased pitch count on throwing shoulder external rotation. Participants averaged 80 pitches and an about 9-14° decrease in shoulder external rotation was seen which has shown to increase the risk of injury in the future (13, 19, 35). Thus, more research is needed to further investigate the impact of fatigue on throwing shoulder kinetics and kinematics to better understand how to prevent arm injuries in baseball pitchers and better understand why there is a decrease in shoulder external rotation with increased pitch count. The RPE scale and Median Frequency indicate a level of fatigue, however further research is needed to investigate if the decrease in the shoulder external rotation is a natural causation to protect the shoulder or if there is a quantifiable amount of shoulder fatigue occurring.

Conclusion

Decreases in median frequency from first to last inning for seven of eight muscles investigated indicating some lower extremity fatiguing were seen, however not to a significant level. There were no significant differences for many variables tested, which literature has not been able to confirm, thus future investigation is needed to better determine the extent to which increasing pitch count may influence a pitcher and their future health.

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Appendix I Demographics Survey

Participant Number

____

Age (yrs)

____

Height (m)

____

Weight (kg)

____

Gender
○ Male
○ Female

Year in School (Ex: Freshman)

____

What arm do you throw with (Specify Right or Left)

____

How do you pitch from the rubber?

- Wind-up
- Stretch

Years of Experience

____

Highest level of competition

____

Have you ever experienced an injury that caused you to miss play in the past 12 months? (Please specify what & when)

____

Have you experienced an injury that required surgery in the past 12 months? (Please specify what & when)

____

Appendix II RPE Scale Survey

RPE after Inning 1

- 0: No exertion, at rest
- 1: Very light
- 2-3: Light
- 4-5: Moderate, somewhat hard
- 6-7: High, vigorous
- 8-9: Very hard
- 10: Maximum effort, highest possible

RPE after Inning 2

- 0: No exertion, at rest
- 1: Very light
- 2-3: Light
- 4-5: Moderate, somewhat hard
- 6-7: High, vigorous
- 8-9: Very hard
- 10: Maximum effort, highest possible

RPE after Inning 3

- 0: No exertion, at rest
- 1: Very light
- 2-3: Light
- 4-5: Moderate, somewhat hard
- 6-7: High, vigorous
- 8-9: Very hard
- 10: Maximum effort, highest possible

RPE after Inning 4

- 0: No exertion, at rest
- 1: Very light
- 2-3: Light
- 4-5: Moderate, somewhat hard
- 6-7: High, vigorous
- 8-9: Very hard
- 10: Maximum effort, highest possible

RPE after Inning 5

- 0: No exertion, at rest
- 1: Very light
- 2-3: Light
- 4-5: Moderate, somewhat hard
- 6-7: High, vigorous
- 8-9: Very hard
- 10: Maximum effort, highest possible

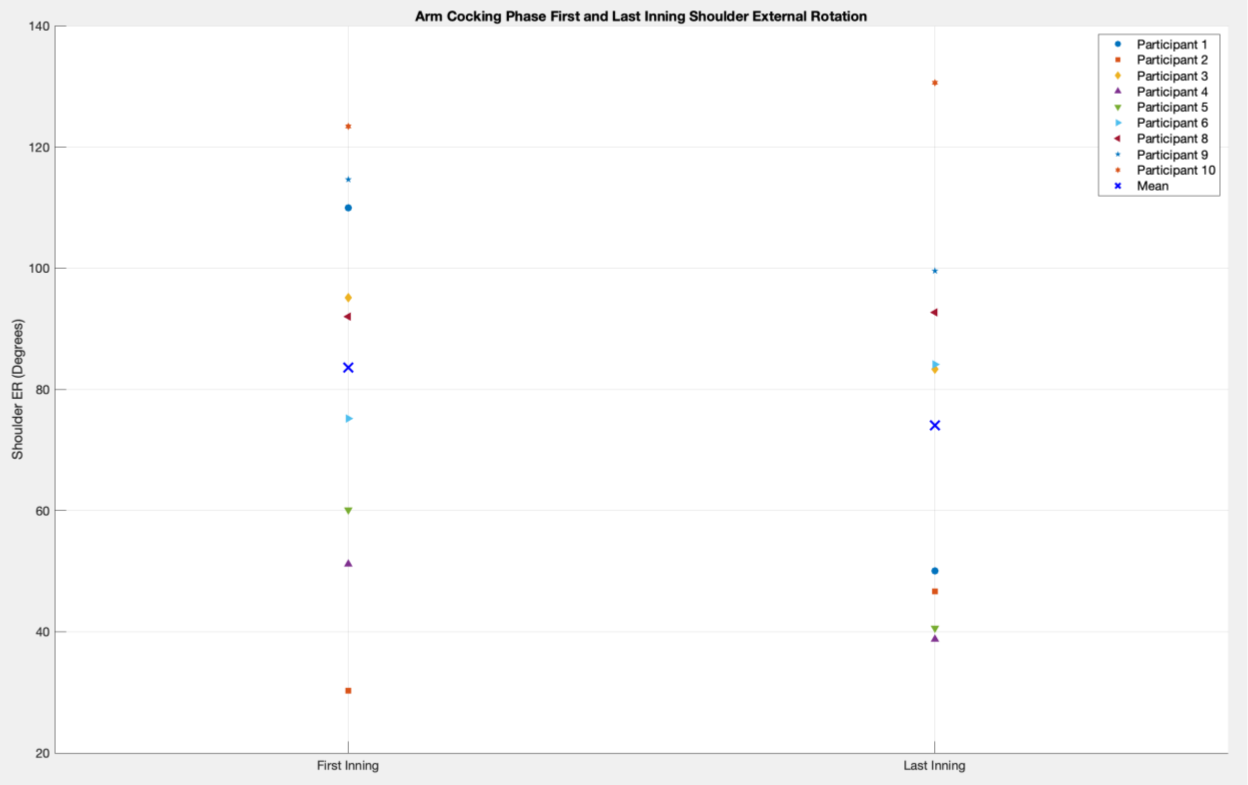
RPE after Inning 6

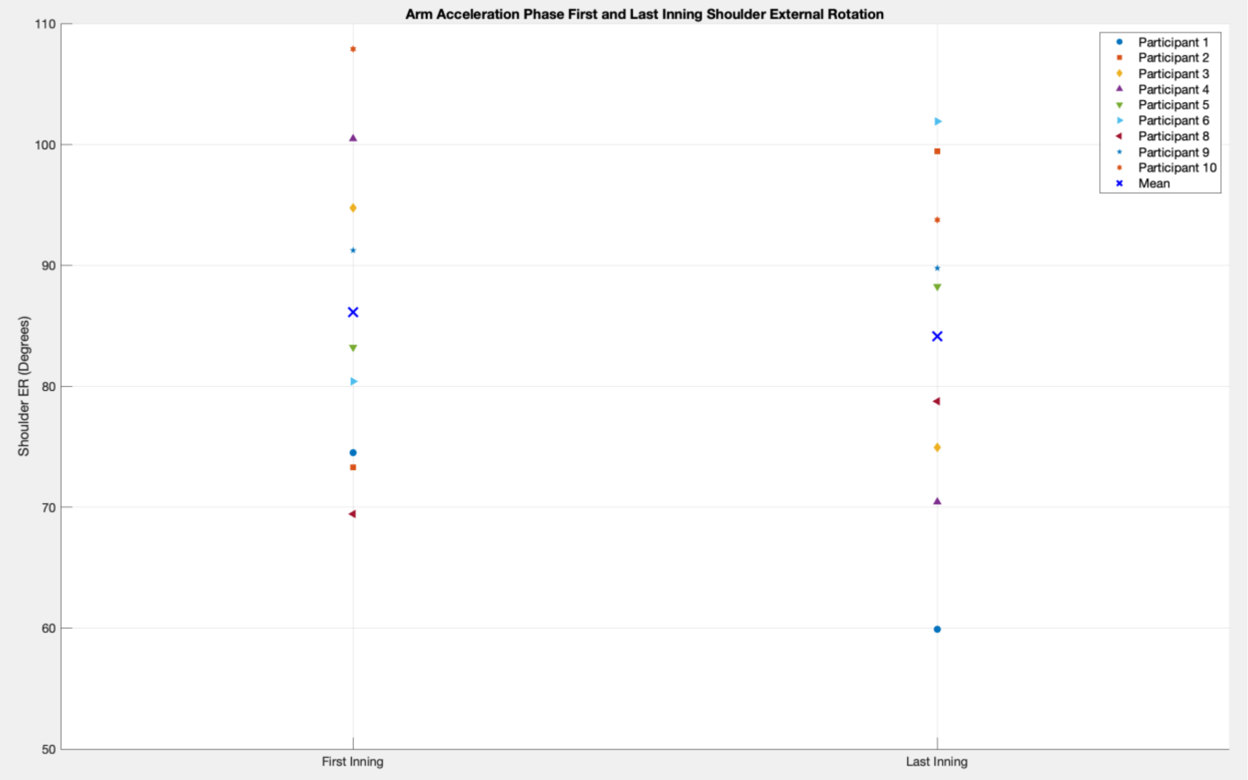
- 0: No exertion, at rest
- 1: Very light
- 2-3: Light
- 4-5: Moderate, somewhat hard
- 6-7: High, vigorous
- 8-9: Very hard
- 10: Maximum effort, highest possible

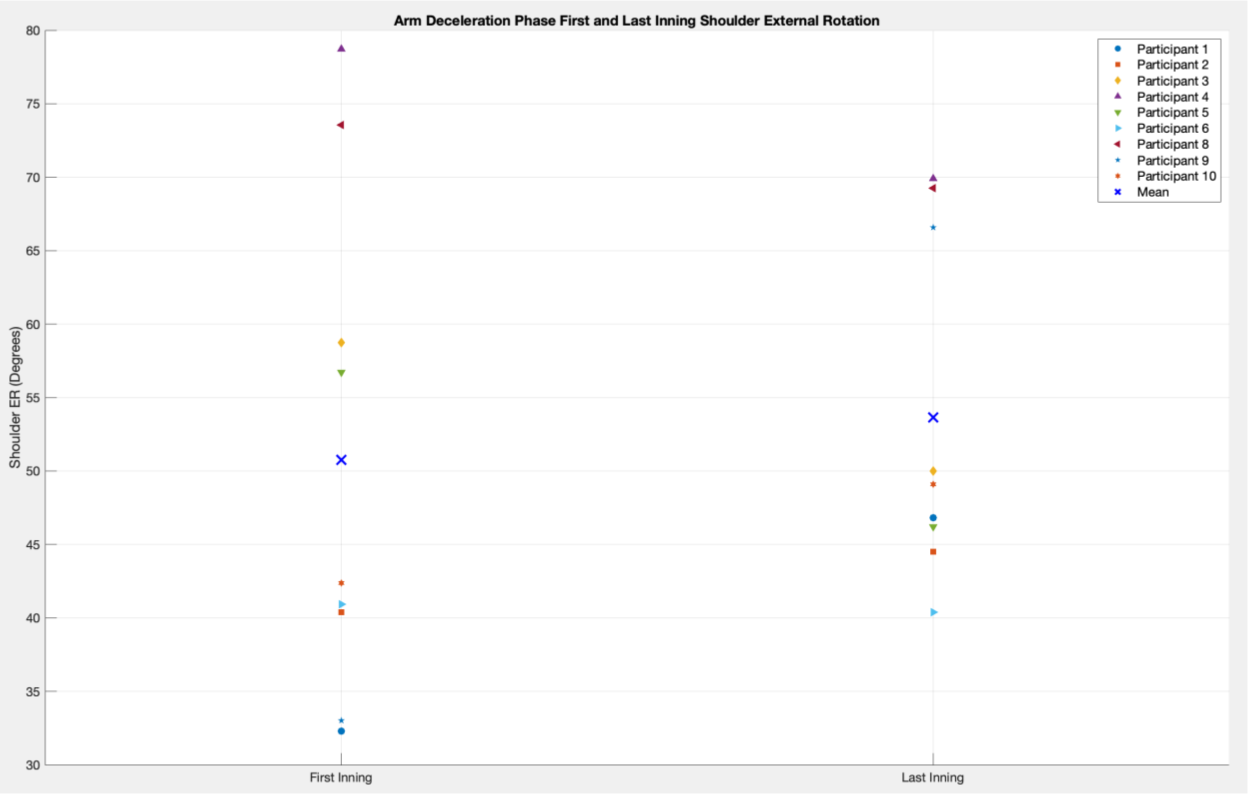
RPE after Inning 7

- 0: No exertion, at rest
- 1: Very light
- 2-3: Light
- 4-5: Moderate, somewhat hard
- 6-7: High, vigorous
- 8-9: Very hard
- 10: Maximum effort, highest possible

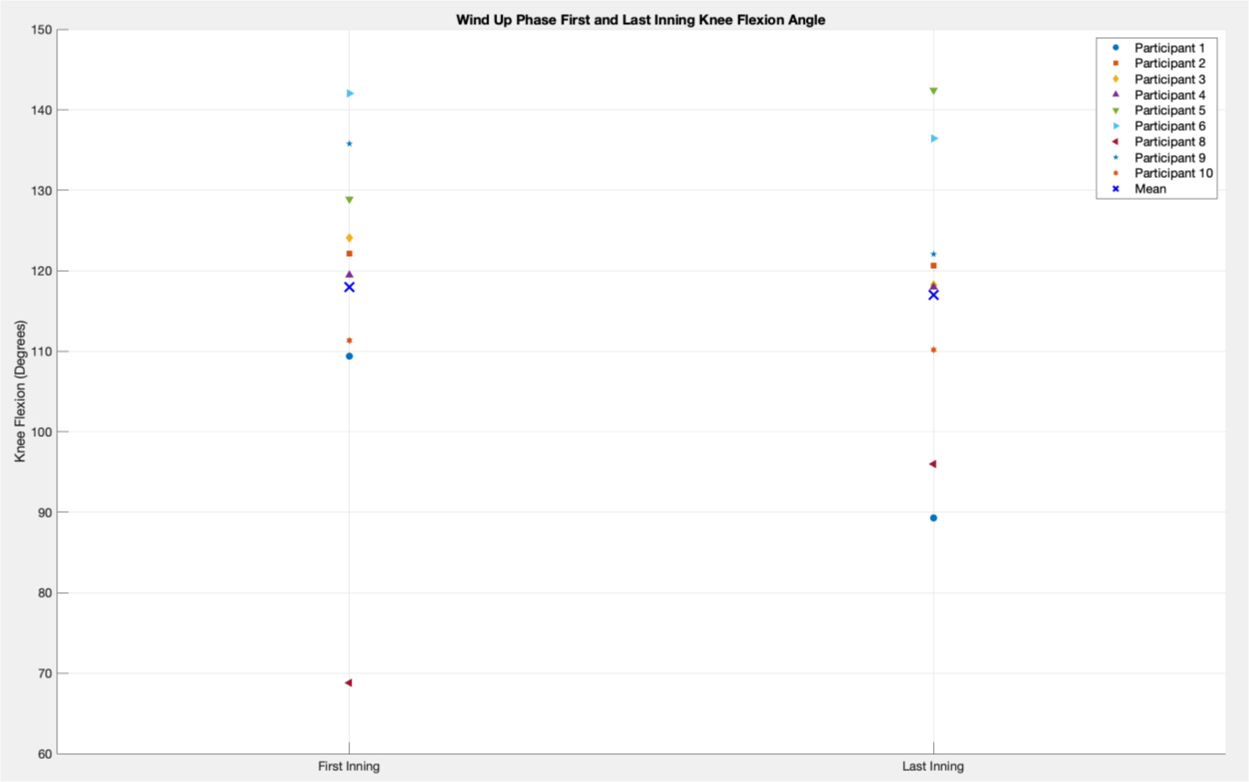
Appendix III First and Last Inning Mean Shoulder External Rotation Figures

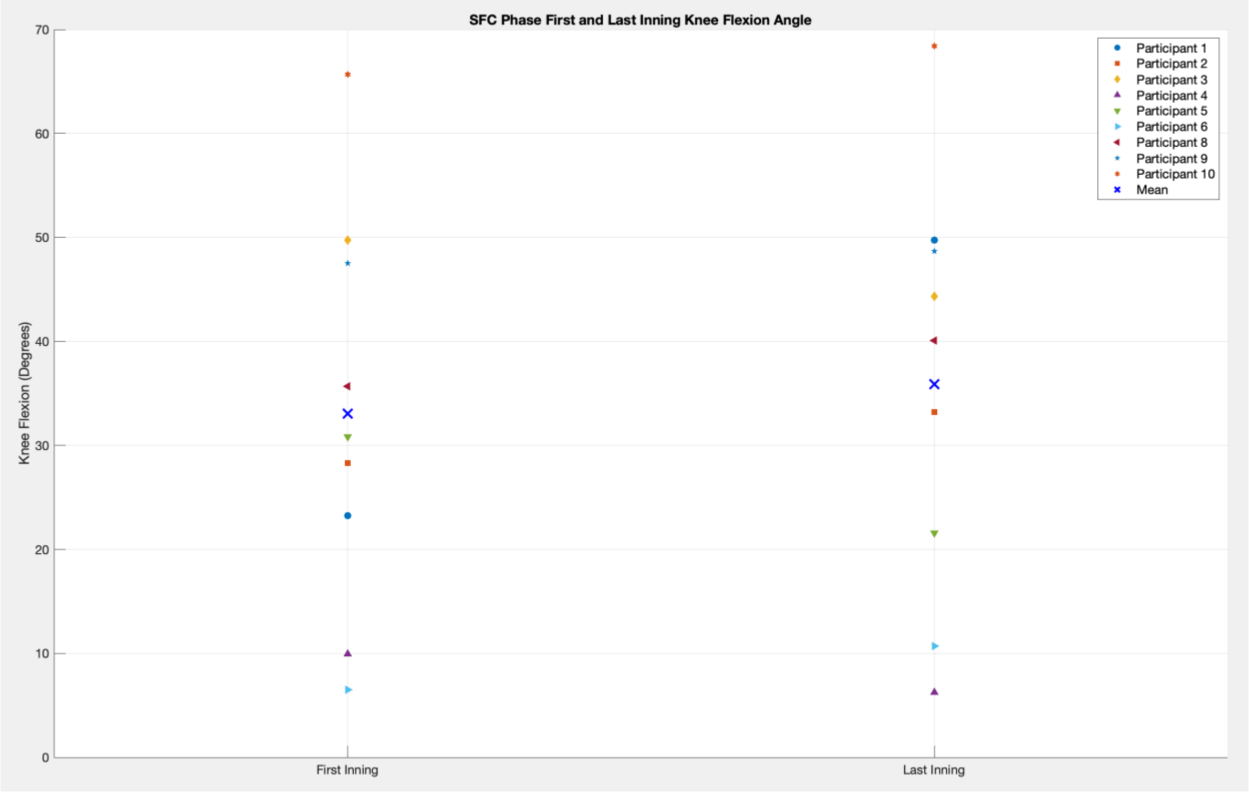


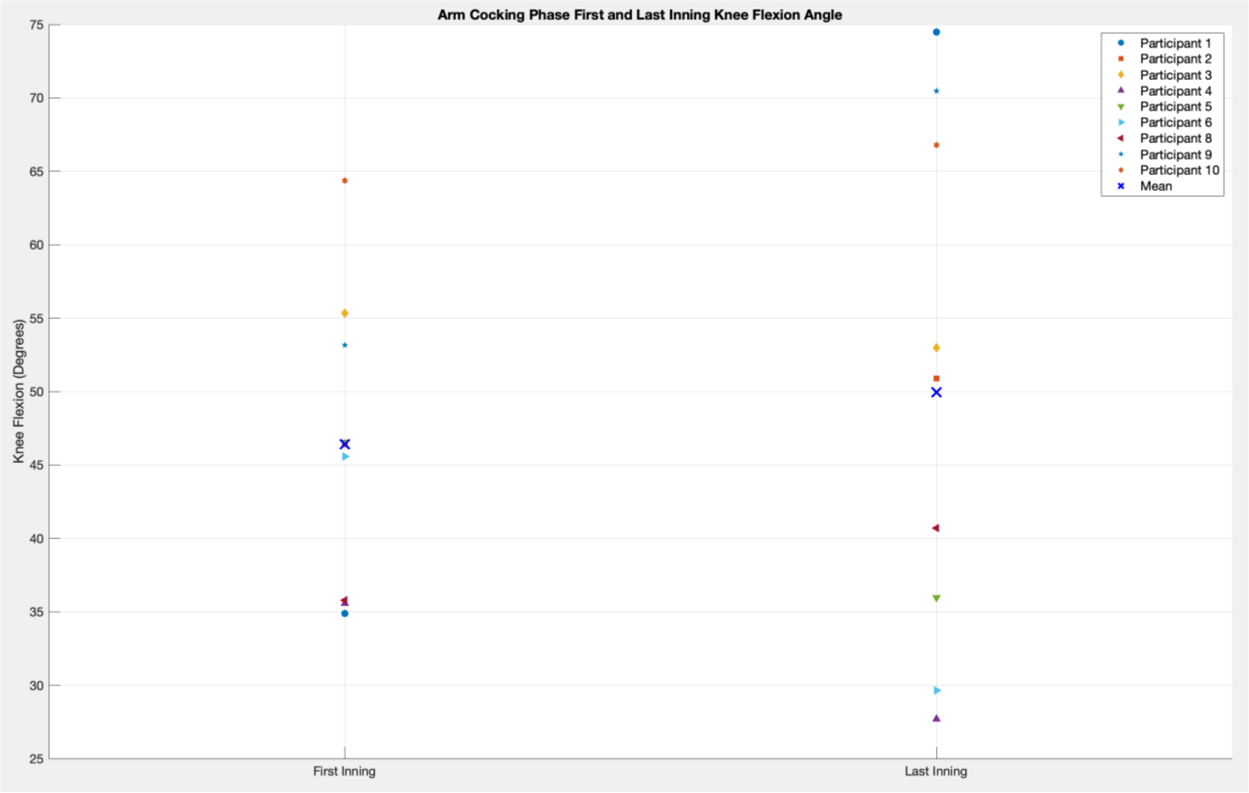


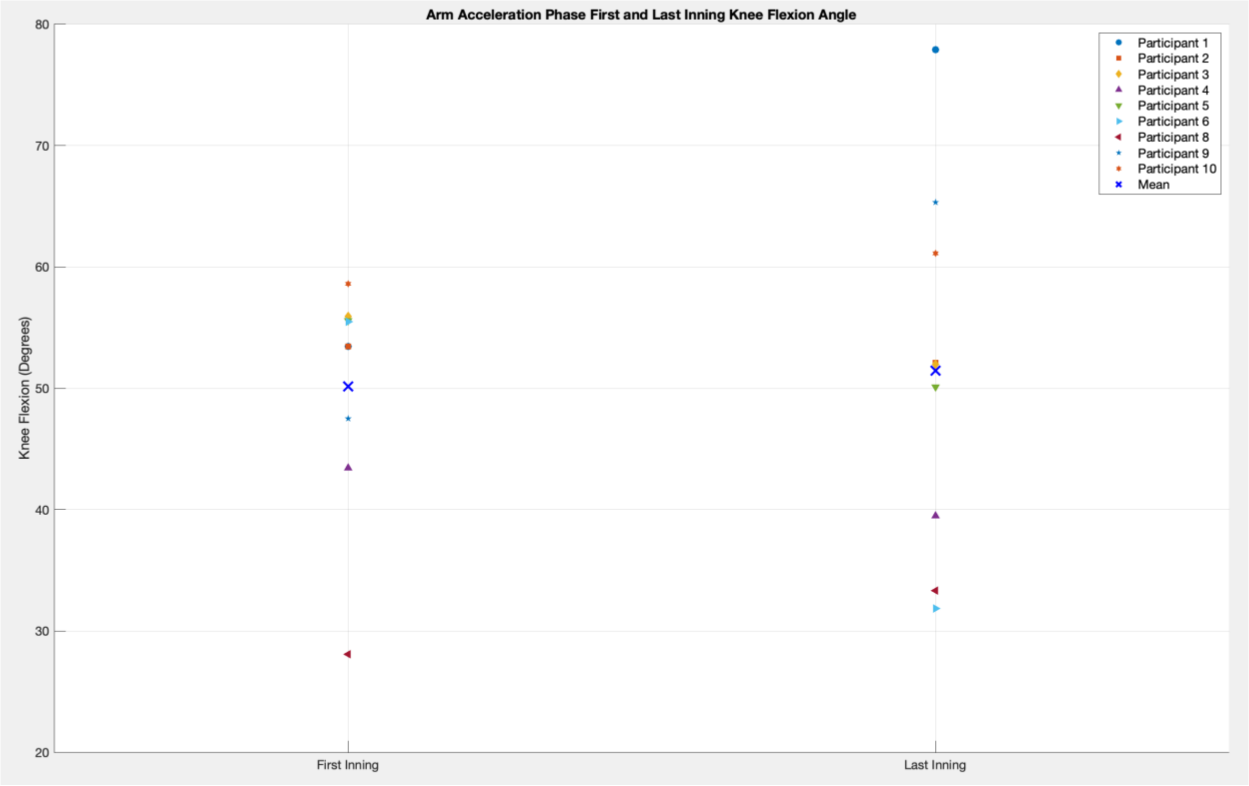

Arm Deceleration Phase First and Last Inning Shoulder External Rotation
Shoulder ER (Degrees)
80
75
70
65
60
55
50
45
40
35
30
First Inning
Last Inning
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 8
Participant 9
Participant 10
Mean

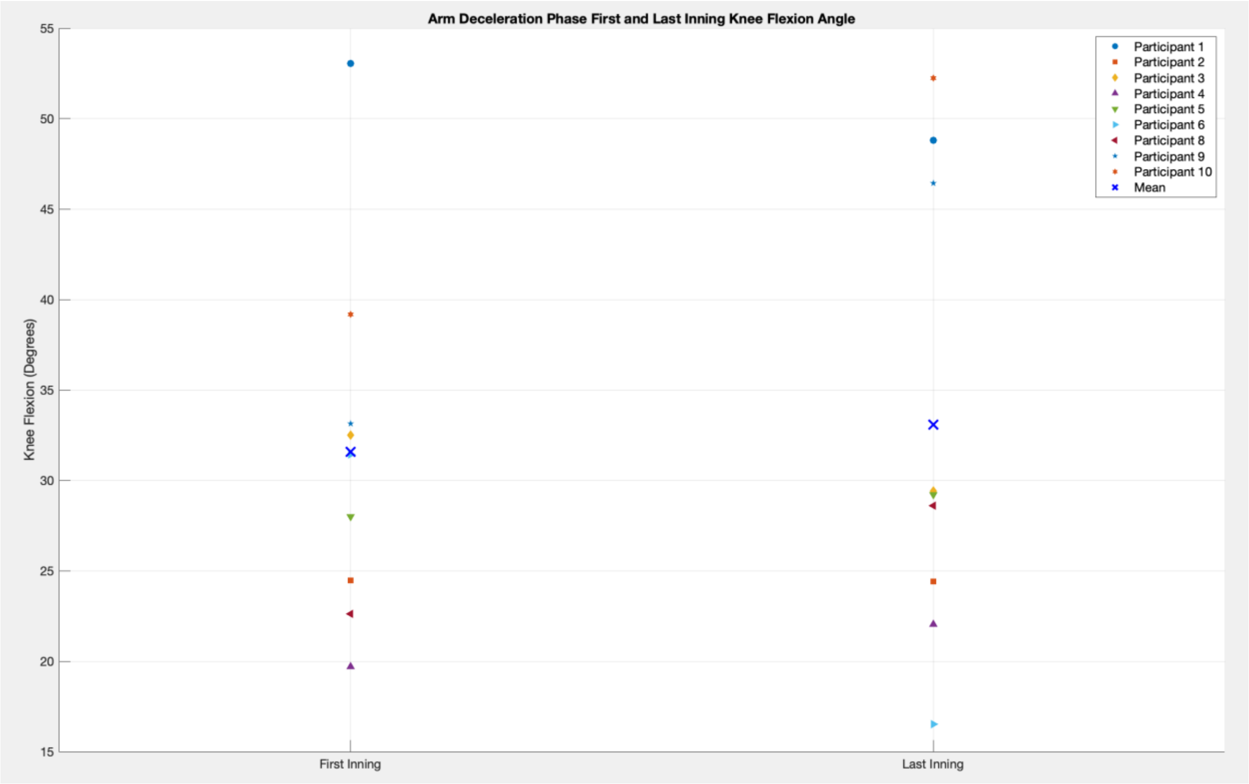
Appendix IV First and Last Inning Mean Knee Flexion Angle Figures

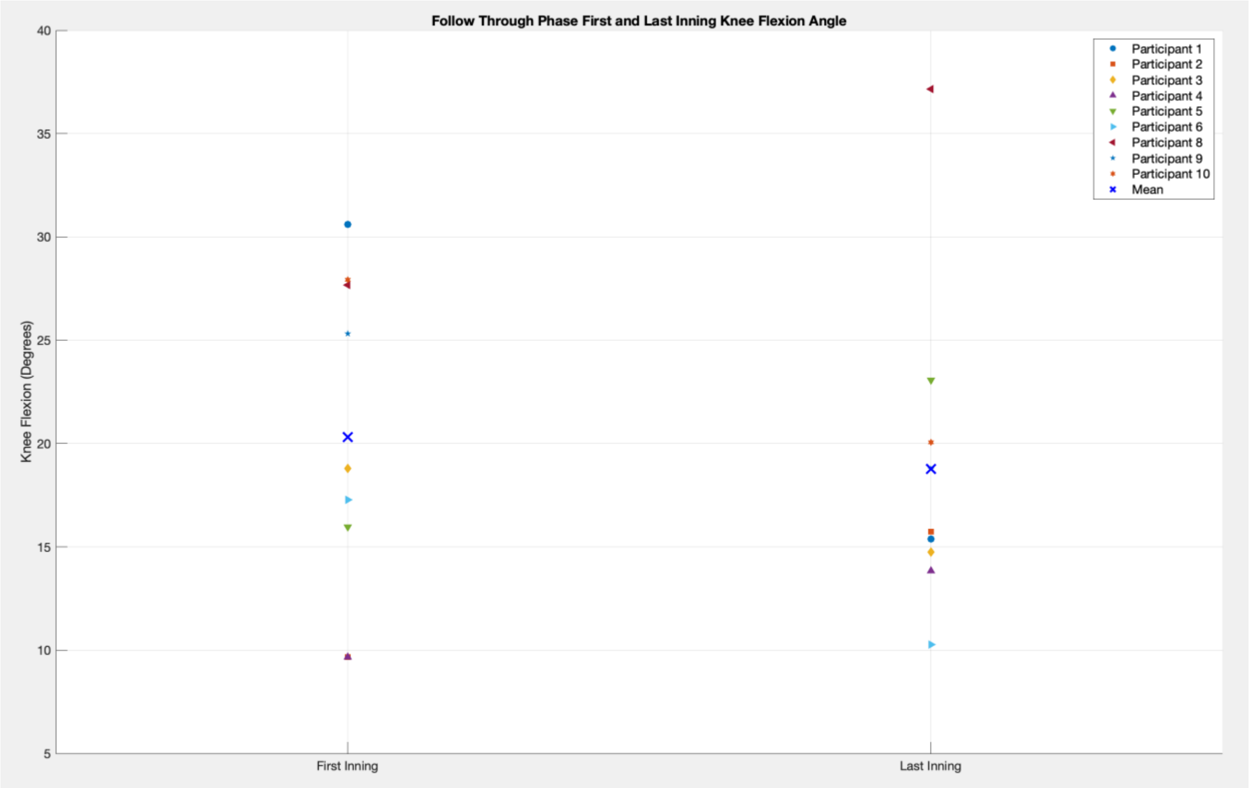





Arm Cocking Phase First and Last Inning Knee Flexion Angle
Knee Flexion (Degrees)
75
70
65
60
55
50
45
40
35
30
25
First Inning
Last Inning
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 8
Participant 9
Participant 10
Mean


Arm Acceleration Phase First and Last Inning Knee Flexion Angle
Knee Flexion (Degrees)
80
70
60
50
40
30
20
First Inning
Last Inning
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 8
Participant 9
Participant 10
Mean


Arm Deceleration Phase First and Last Inning Knee Flexion Angle
Knee Flexion (Degrees)
55
50
45
40
35
30
25
20
15
First Inning
Last Inning
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 8
Participant 9
Participant 10
Mean


Follow Through Phase First and Last Inning Knee Flexion Angle
Knee Flexion (Degrees)
40
35
30
25
20
15
10
5
First Inning
Last Inning
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 8
Participant 9
Participant 10
Mean

Appendix V IRB Approval Letter

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board
Ω ιλλισΒυιλδινγ •ΜαιλΣτοπ 682
600 Μοψε Βουλεϖαρδ •Γ ρεενϖιλλε, ΝΧ 27834
Οφφιχε **252-744-2914** •Φαξ **252-744-2284** •
rede.ecu.edu/umcirb/

Notification of Amendment Approval

From: Biomedical IRB
To: Jeremy Praski
CC: Nicholas Murray
Date: 11/3/2023
Re: Ame1 UMCIRB 23-001575
UMCIRB 23-001575
Influence of Lower Extremity Muscle Fatigue on Baseball Pitching

Your Amendment has been reviewed and approved using expedited review for the period of 11/3/2023 to . It was the determination of the UMCIRB Chairperson (or designee) that this revision does not impact the overall risk/benefit ratio of the study and is appropriate for the population and procedures proposed.

Please note that any further changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. A continuing or final review must be submitted to the UMCIRB prior to the date of study expiration.The investigator must adhere to all reporting requirements for this study.

Approved consent documents with the IRB approval date stamped on the document should be used to consent participants (consent documents with the IRB approval date stamp are found under the Documents tab in the study workspace).

The approval includes the following items:

Description:
Robert Langston, Amber Hancock, and Robert Birdsong added to the study team

For research studies where a waiver or alteration of HIPAA Authorization has been approved, the IRB states that each of the waiver criteria in 45 CFR 164.512(i)(1)(i)(A) and (2)(i) through (v) have been met. Additionally, the elements of PHI to be collected as described in items 1 and 2 of the Application for Waiver of Authorization have been determined to be the minimal necessary for the specified research.

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418