THE EFFECTS OF CONSECUTIVE SOFTBALL WINDMILL PITCHES ON COORDINATION PATTERNS AND VARIABILITY, MUSCULAR STRENGTH, AND PITCHING PERFORMANCE

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Upper and lower extremity musculoskeletal injuries occur at a similar rate in softball pitchers. Most of these injuries can be considered chronic in nature, which may result in symptoms being treated instead of considering the underlying mechanism for injury. Previous literature has primarily focused on discrete values such as joint ranges and kinematic peaks. The primary purpose was to examine inter-segmental and intra-limb coordination of the softball windmill pitch throughout a simulated game of softball and to determine if variability of these patterns change throughout multiple pitch counts. The secondary purpose is to identify if a difference between pre-pitching and post-pitching strength can be detected to determine if muscular fatigue, as defined by the inability to sustain the expected power output around a joint, has occurred. Pitching performance, defined as pitch velocity and accuracy, were also assessed. A total of 14 softball pitchers (17.9±2.3 years, 166.4±8.67 cm, 72.3±12.6 kg) successfully completed all strength assessments and pitching sequence. Pitchers completed strength assessments of the at baseline and immediately after a pitching sequence consisting of 105 fastballs. Vector coding was used to measure coordination and variability of Drive Leg Thigh v Pelvis, Pelvis v Torso, Pelvis v Humerus and Humerus v Forearm. Paired t-test or Wilcoxon Signed Ranks test was used to determine change in muscular strength. One-way repeated measures analysis of variance was performed to establish if differences in pitch velocity or accuracy varied between innings.

Appropriate order parameter to encapsulate the behavior of the windmill pitch could not be established due to lack of fatigue or incorrect coordinative structures measured. Results demonstrated a significant increase in stride leg knee extension and trunk flexion peak torque, as percent body weight, after consecutive pitches. Differences were seen in pitch velocity but not accuracy across innings. While this study did not demonstrate the negative effects of consecutive pitching that were expected, results can provide a foundation for future research into windmill pitch mechanics to assist with injury prevention and performance optimization.

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PREFACE

I would like to thank those who have helped me throughout this process. First, I thank faculty, past and present, at the Neuromuscular Research Laboratory for affording me the opportunity to continue my educational journey. Thank you to my dissertation committee who has aided me through this process and their willingness to let me forge my own path. Faculty in the Athletic Training Education Program deserve my gratitude for supporting my ultimate career goals, giving me a chance to work with their students and for all their guidance and encouragement. Heartfelt thanks to Dr. Kevin Conley who has been there from the very beginning and is my best role for mentor, teacher and athletic trainer. A special thank you to my fellow graduate students for your help, patience and support both in and out of the lab.

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1.0 INTRODUCTION

Fifty percent of high school softball pitchers have been reported sustaining an injury during a single season.[1] Almost 73% of collegiate softball pitchers get injured during one season, with 31.7% of those experiencing more than one injury.[2] Powell and Barber-Foss have reported that female softball players sustain injuries at a greater rate than baseball players.[3] To date, there is limited research on the kinematics and coordination of movement throughout the softball windmill pitch and how it relates to injury and performance.

In the 1981-82 season, 7,465 total softball athletes were a member of a National Collegiate Athletic Association (NCAA) roster. That number has grown to 19,628 collegiate softball athletes by the 2014-15 season.[4] Despite softball's participation numbers increasing, softball is often grouped with baseball as "overhead athletes" when describing shoulder pathology and rehabilitation.[5,6] Categorizing both sports together may not be appropriate because there are several significant differences in the playing conditions and kinematics of the players involved, especially when considering the pitcher position. Softball plays on a smaller field and uses a larger and heavier ball, but the primary difference between baseball and softball are in the pitching mechanics.[7] Softball pitchers employ a windmill style movement in which the humerus remains in the same plane as the body and force comes from adduction of the arm across the body, whereas baseball pitchers use an overhand throw where the arm is in an abducted position allowing force to be generated through rapid internal rotation of the humerus.[8]

The most common injuries to softball pitchers are directly related to the kinetics and kinematics of the windmill pitch; occurring as a consequence of the repeated execution of the movement and the culmination of the forces acting upon the structures of the body.[9] Leahy describes this as cumulative injury disorder, in which the stress applied to tissue is related to the number of repetitions multiplied by the force applied.[10] Repetitive stress is amplified because, unlike baseball pitchers, there is no maximum pitch count or mandatory days of rest for softball pitchers. The best pitcher on a high school or college softball team will pitch most, if not all, of the games each season.[2] This can result in approximately 1200 to 1500 pitches being thrown in a three day tournament for a windmill pitcher, as compared to 100 to 150 for a baseball pitcher.[7] Execution of the windmill pitch requires the systematic coordination of multiple body segments to consistently throw high velocity and accurate pitches.[11] The potential for changes in coordination and production of maladaptive movement strategies, as a consequence of fatigue associated with repeated pitching, may impact performance and put a pitcher at an increased risk for future injury. Therefore, establishing coordination patterns and their potential variability over consecutive pitches sets a baseline for future prospective research to investigate whether dysfunctional coordination patterns, having reduced or excessive variability, contributes to risk of injury.

1.1 EPIDEMIOLOGY OF SOFTBALL INJURIES

Extensive research has been undertaken examining baseball pitchers' injury and risk factors associated with the high velocity mechanics of overhand pitching.[12-16] As a consequence of the high stress placed on the pitching arm in baseball,[13] the governing body for each level of play have established controlled pitch counts and required days off between innings pitched at all levels of play. Conversely, softball has no pitch counts and no regulations have been set to limit the numbers of days softball pitchers can play. The absence of any regulations restricting the pitch count for softball may be as a consequence of anecdotal suggestions that the softball pitch is considerably less stressful to the upper extremity of pitchers.[17] The requirement to generate large torques and high velocity movements in the windmill pitch are responsible for the incidence and types of injury sustained.[18] The rapid motion of the windmill pitch results in high ball velocities, while placing excess stress on the anterior capsule and biceps labrum of the shoulder.[19] Resistance to the distraction forces at the shoulder during the windmill pitch have been reported to achieve between 80-95% of the normalized values for overhand (baseball) pitching.[18] With no limitations on the volume of softball pitches, high forces at the shoulder can impact the number of injuries observed.

Overall softball injury rates have been reported to be between 2.7 practice injuries and 4.3 game injuries per 1000 athlete-exposures.[20] As the arm is brought down from the overhead position during the windmill pitch, it reaches a velocity greater than 5,000°/ sec, which increases forces at the upper extremity; ending with an abrupt deceleration of forces as the arm passes the lateral thigh.[18,21] In a study of high school softball pitchers, 50% of all pitchers experienced an injury over one season of play.[22] Pitchers were 2.6 times more likely to sustain an upper extremity (shoulder or elbow) injury than a position player.[1] Injuries suffered on the pitching mound have been shown to be significantly more likely to require surgery (injury proportion ratio: 2.64).[22] According to the National Collegiate Athletic Association Injury Surveillance System, 42% of all practice and game injuries occur to the lower extremity while 33% are to the upper extremity. Out of 181 NCAA softball pitchers, 70% reported chronic or overuse injuries with the majority being to the shoulder and low back.[2] Similar proportions of upper and lower extremity injury to softball pitchers may be due to the complex, full body motion of the windmill pitch.

1.2 SOFTBALL WINDMILL PITCH

There are significant biomechanical differences between the underhand windmill style softball pitch and the overhand baseball pitch. In a baseball pitch, the humerus is abducted and maximal acceleration is achieved by internal rotation at the shoulder. Deceleration of the shoulder in baseball pitching is due to eccentric shoulder muscle activation.[23] The softball windmill pitch stays primarily in the sagittal plane of the body and the arm is accelerated due to its adduction across the body, slowing of the arm occurs after the arm passes the trunk.[8]

When analyzing the windmill pitch, it has been described as having six phases, based on a clock face, from the side view of a pitcher: Phase 1 (windup) begins with a counterclockwise downward movement coming back to a 6 o'clock position, Phase 2 (preparatory) initiates upward movement from 6 to 3 o'clock, Phase 3 (acceleration) continues upward movement from 3 to 12 o'clock, Phase 4 (power) starts humerus acceleration from 12 to 9 o'clock, Phase 5 (release) corresponds to movement from 9 o'clock to ball release, and phase 6 (deceleration) parallels movement from ball release to completion of the follow-through motion.[24] Understand basic mechanics of individual sports will help develop specific training strategies to prevent future injury.

1.2.1 Risk of injury

The identification of potentially modifiable risk factors is vital to injury prevention. Softball pitchers are at risk for upper extremity injuries because of the strain placed on the shoulder and elbow while pitching. Consistent repetition of accurate and high velocity pitching is key to an athlete's success. However, the resulting microtrauma associated with repeatedly performing these type of movements is also a source of injury, causing the majority of injuries to be noncontact.[25] Even when players and coaches strive for a balance of playing time and rest, a softball pitcher can pitch between 86 to 139 innings per season.[17]

Minimal intrinsic risk factors and mechanisms related to softball pitching injuries have been established in published literature. The musculoskeletal system exhibits a high amount of synchronous activity to produce the rapid motion of the windmill pitch.[26] From the initiation of the windup, the arm accelerates through its full range of shoulder flexion due to actions of the rotator cuff, pectoralis major, anterior and posterior deltoids and serratus anterior musculature. At various time points within this motion, intensity of muscular activity has been reported to range between 45 to 100% of maximal capacity.[24] Muscle activation, in addition to velocity of movement, influences the magnitude of load placed on the shoulder and elbow joints.[27] During execution of the windmill style pitch, maximum compression forces at the shoulder and elbow have been seen as high as 70 to 98% of body weight.[18] The torque occurring at the elbow is largely due to having to control elbow extension and then initiate elbow flexion.[9] As a consequence of the windmill style delivery, a large demand is placed on the biceps labrum complex to simultaneously produce elbow flexion in addition to resisting glenohumeral distraction.[18]

A limited number of ligamentous knee injuries occur in softball pitchers, as compared to other female sports, likely due to the decreased stride leg knee adduction angles.[28] However, high numbers of low back and hip injuries have been seen in softball pitchers.[17] Increased stride leg hip adduction angles have been seen during the windmill pitch, which may be a result of decreased stride leg gluteal muscle activation.[28] Weakness in hip musculature has been shown to also play a role in low back pain.[29] Improper pelvic stabilization may increase compressive force on the lumbar vertebrae, contributing to the number of low back injuries.[30] Decreased muscle activation of musculature surrounding the pelvis, causing altered lumbopelvic movement, disrupts efficient transfer of energy up the kinetic chain by altering timing of torso rotation.[31] Disruption of the kinetic chain can cause a 23-27% increase in loads experienced at the shoulder and elbow, as seen in overhead athletes.[32] Altered muscle activation or weakness can be a result of fatigue, over the course of multiple innings, influencing a softball pitcher’s ability to maintain proper mechanics and safely dissipate forces throughout the throwing motion.[33]

1.3 FATIGUE EFFECT ON PERFORMANCE

Softball pitchers often have to pitch back to back games within a day and on consecutive days. The high volume of pitches has the potential to cause fatigue and increase risk of injury.[34,35] Fatigue can generally be defined as the inability to maintain muscular performance and strength.[36] Fatigue has been shown to reduce proprioception, increase joint laxity, diminish capacity for shock absorption and delay muscular activation.[37] Fatigue influences the ability to maintain proper mechanics and the muscles’ ability to safely dissipate forces throughout throwing to decrease unnecessary joint stress.[33]

The effects of fatigue on performance and risk of injury is a popular topic in sports medicine.[38-40] The sequential and coordinated movement of body segments is largely influenced by muscular forces which produce distinctive patterns of segmental movement.[41] If these muscles become fatigued during activity, changes in movement patterns will likely be seen. The effects of fatigue on lower extremity mechanics has been studied extensively. Muscular fatigue has been shown to decrease postural control[42,43] and alter lower extremity kinematics during a stop-jump task.[44,45] It has been proposed that the impact of fatigue on lower extremity neuromuscular control contributes to the large number of non-contact anterior cruciate ligament (ACL) injuries in female athletes.[46-48] A decrease in muscular strength due to fatigue has been proposed to also increase susceptibility of upper extremity injury.[49,50] Decreased force production is one component of muscular fatigue.[51] Fatigue, observed as a significant loss of arm strength, has been observed in baseball players after pitching approximately seven innings, or throwing 100 pitches.[52] Injury risk may be greatest at the end of a practice or game or the end of a competitive season, as fatigued muscles are more susceptible to injury.[53,54]

Shoulder muscle fatigue has been shown to alter kinematics; deviations away from normal movement patterns leads to increased loading of tissue as well as kinematic changes in sport specific movements.[55] In a study of Division I collegiate baseball pitchers, changes in mechanics and variability in movement were seen between pitches thrown at the beginning and end of innings and games.[35] Hip extension, elbow height and shoulder external rotation showed the most significant changes.[35] In the final two innings pitched, baseball pitchers have been observed as having a more vertical trunk position.[56] When assessing segmental coordination, Forestier and Nougier found that after fatiguing the upper extremity there was increased rigidity of the throwing arm pattern that resulted in decreased accuracy.[57] Rigid movement patterns observed after fatigue removed the temporal delay between the elbow and hand, decreasing end velocity.[57] Similar compensating strategies may also be observed in the throwing arm during the windmill pitch as well as whole body movement patterns prior to ball release.

Bradbury and Forman attempted to quantify the effect of pitch count on performance in major league baseball, finding a negative relationship between pitch count and subsequent performance.[58] Similar decreases in ball velocity have been seen in collegiate baseball pitchers.[35,56] A combination of decreased muscular strength and altered mechanics due to fatigue may put athletes at a higher risk for pain and injury. A 36 fold increase in injury risk has been reported in baseball pitchers who competed in a fatigued state.[59] Lyman et al.[60] found a relationship between number of pitches thrown by youth pitchers and elbow or shoulder pain. Increased age and weight were associated with elbow pain. Arm fatigue and throwing more than 75 pitches per game were risk factors for both elbow and shoulder pain.[60] Decreased pitch velocity and upper extremity pain associated with fatigue may be a result of changes in movement patterns.

Adaptations in coordination due to muscular fatigue have been seen with changes in muscle activation patterns and subsequent joint motion while hopping,[61] changes in proximal and distal variability of movement during a lifting task,[62] and with intersegmental coordination with forceful ball throwing.[57] Coordination adaptations in movement patterns and muscle activation strategies are adopted to compensate for the accumulated fatigue and to maintain power output.[63] The absence of a temporal delay between connected segments seen when fatigue occurs, creates a rigid movement organization. In the windmill pitch, experienced players may be able to use a robust segmental coordination throughout their whole-body movement, which allows them to maintain ball velocity, in spite of the muscular fatigue development.

1.4 KINETIC CHAIN

The kinetic chain is a coordinated sequencing of activation, mobilization, and stabilization of body segments to produce a dynamic, goal-directed activity.[64,65] An effective kinetic chain is defined by optimized anatomy (strength, flexibility, and power generation), well developed, task specific motor patterns and sequential generation of forces appropriately distributed across motions.[66] The effective generation, transfer and control of energy within and throughout the movement system can enhance or maintain performance and reduces the risk of injury. Successful completion of the softball windmill pitch occurs with the effective transfer of momentum from proximal to distal segments, increasing their angular velocity to maximal velocity of the most distal segment.[65]

Alexander and Haddow examined the softball windmill pitch and concluded there was a definite proximal to distal sequencing, with deceleration of the proximal segments prior to ball release.[67] A critical component required to maximize the contribution of each segment along the kinetic chain is the proper timing of the rotation between the pelvis and rotation of the upper trunk.[13] If proper timing does not occur, the contributions of the two core segments are lost.[68] Sequential rotation of the pelvis, torso and arm creates a rotational lag between segments. This rotational lag allows for effective muscle force production and increased exploitation of passive generation of forces through the stretch-shortening cycle.[69] Increased ability to develop force and motion at the proximal segment provides maximal force at the distal end according to the summation of speed principle.[65] This can be seen in skilled pitchers who often put their stride leg away from their pitching arm, providing a longer time period over which force can be generated at the legs and trunk.[41] Ineffective movement disrupts transfer of momentum, forcing compensatory changes in mechanics to maintain ball velocity.[70,71] Ball accuracy and maximum velocity are a result of proper coordination of movement.[71] In the kinetic chain, motion of one segment must influence the motions of adjacent segments. The success of a softball pitcher is in the ability to repeat this proximal to distal sequence of movement over multiple innings and games. Rather than focusing on the mechanics of single joints and segments, the coupling and relative timing, or coordination, between segments should be considered.

1.5 COORDINATION OF MOVEMENT

Previous methods of analyzing movement have been influenced by a mechanistic view.[72] This perspective views time as linear and evolutionary, managing segments to maintain peak function.[73] Studies that investigate single joint or segment kinematics fail to account for the confounding influence of adjacent joints or segments. Coaching techniques that followed this theory focused on one possible correct technique; training focused on specified training, minimizing spontaneous decision making. Performance development in this light does not accurately reflect the relentlessly changing reality of sports. A modern view of human movement explains behavior as kinematic and kinetic parameters that result in intended actions, or coordination. Coordination can be described as the body and limbs' pattern of motion relative to the environment.[74] For example, if we only measure a softball pitcher's stride leg angle at ball release, that singular value may lead us to believe she has good mechanics. However, if we determine that her stride leg is not in line with home plate because she has not fully rotated her pelvis back to neutral, we might conclude that she didn't properly finish her pitch. Compared to single-joint and single-segment kinematics, these inter-joint and inter-segmental coordination analyses may have greater sensitivity to detect subtle kinematic differences with varying mechanical demands.[75]

The human movement system is a highly intricate network of co-dependent sub-systems that are composed of a large number of interacting components. A dynamical systems approach recognizes the high number of available biomechanical degrees of freedom must be reduced through the formation of coordinative structures, which are functionally linked to satisfy task demands.[74] Temporary formation of these coordinative structures occurs through self-organization. The principle of self-organization assumes that coordination emerges from interacting elements that adapt to changing internal and external conditions without explicit prescription of this pattern.[76] [77] Movement patterns develop as a function of changing constraints placed upon the body's system. Constraints can be viewed as boundaries or limitations that apply restrictions to the organization of movement at different levels of the body system.[78] The major task in the production of goal oriented coordination is to constrain the extreme number of possible body movements, or degrees of freedom.[79] This redundancy, a direct consequence of the large number of mechanical degrees of freedom, is built in to human movement to allow for adjustments in movement enabling response to internal and external stimuli, such as fatigue or environmental changes. To reduce the number of degrees of freedom, self-organization occurs as a consequence of the interactions between environmental, biomechanical and morphological constraints; enabling stable movement patterns.[80] In this view of human movement, an athlete does not need to know the solution of a new task at hand; the interacting constraints will eventually produce the correct response.

Newell categorized these constraints into organismic, environmental and task.[81] Organismic constraints are endogenous to an athlete's neuromuscular system. Environmental constraints are more challenging to manipulate because they pertain to the spatial and temporal layout of the surrounding world which act on an athlete. This can include temperature, wind or gravitational forces. Task constraints are more specific, including goals, rules of the sport and equipment used during performance. The impact of task constraints is largely dependent on the motor activity being performed, causing an individual to use specific muscles and joints to produce a specific movement pattern to produce goal/task oriented performance. These constraints do not prevent movement but alter the coordination patterns used to produce a successful performance.

Condensation of the degrees of freedom into an organized pattern allows the complexity of a system to be described in order parameters. Order parameters define the overall behavior of a system and allow coordinated patterns of movement to be reproduced and distinguished from other patterns.[82] Reorganization of behavior, leading to significant changes in the overall pattern of a system, are precipitated by control parameters.[83] Control parameters, such as speed or force, freely change according to the characteristics of the action situation. There is an enormous range of coordination patterns to select from, yet there are only a few preferred modes for each task. Attractor states are the preferred modes a system has an affinity for, lending to a highly ordered and stable system, leading to consistent movement patterns for specific tasks.

Constraints placed on an individual's movement system are dynamic, changing continously. Therefore, optimal patterns of coordination may need to evolve and adapt accordingly in response to changes in the constraints acting on the system. For example, a softball pitcher playing in a weekend tournament will have to alter the aim of her pitch depending on the height of the batter. Accumulation of innings pitched may cause muscular fatigue or increasing temperatures throughout the day also add stress to the central nervous system, muscular system and cardiovascular system requiring the athlete's motor system to adapt.[84] Reorganization is repeated by continually searching for an optimal coordination pattern for the constraints at hand, rather than repeating one particular solution.[85] The adaptative nature of the dynamics of coordination allow for variabilty in movement patterns for stability in performance parameters.

1.5.1 Variability of coordination

Coordination involves the movement of segments in specific time and space, utilizing various muscles to produce a correct movement pattern to meet the demands of a given task.[86] Formation of movement patterns involves bringing the multiple degrees of freedom at each level into proper relations through the redundancy in the motor system.[74] Dynamic tasks do not prescribe a single, specific coordination pattern allowing an individual to select from multiple motor patterns to complete a task.[87] Variability and stability in coordination is observed as individuals attempt to find functional, goal-directed patterns of behavior for each unique performance.[88] Performance tasks meant to achieve a singular consistent outcome, such as softball pitching, requires variability in its motor pattern in order to adapt to task demands without compromising end performance.

Traditionally, variability is thought of as error, or 'noise' in the movement system, and must be overcome for optimal performance.[89] However, variability in coordination in inherent in functional and stable systems that are adaptable and able to effectively use multiple degrees of freedom to optimize task performance.[87] Stability enables the ability to find adaptive coordination patterns when perturbations occur, to keep from destabilizing, or the capability to quickly return to its original state after perturbation.[90] Movement variability is not detrimental as long as the critical end point parameters remain stable, allowing for constant performance outcome.[91] Behavioral flexibility, seen in response to changes in the task, result in the emergence of new behaviors to enhance task performance.[89,92] For example, in softball batting, an athlete utilizes information from the incoming ball to regulate initiation of key propulsive movements.[93] Variability should then be thought of as adaptability. Flexibility in the movement system is regarded as functional because the biomechanical degrees of freedom allow for flexibility of different movement patterns to achieve the same outcome.[88]

Too much or too little variability within movement patterns can be indicative of injury of pathology.[94] Rigid movement patterns, decreasing variability in the attempt to simplify control, has been observed in multi-segment movements after fatigue.[57] Decreased variability reduces the anatomic area over which normal loads are applied during repetitive tasks, and when applied over many cycles, may result in overuse injury.[94] Cumulative micro-trauma injuries, known as overuse or chronic injuries, result from a high number of repeated low magnitude impacts.[94] Biceps tendonitis may develop in a softball pitcher who utilized the exact same rigid movement pattern, continuously placing the same stress loads on the biceps. Flexibility in movement patterns constantly varies the point of force application onto different anatomical surfaces, reducing the risk of injury. Variations in coordination may allow for distribution of stresses more broadly between different tissues, reducing the cumulative load on any particular surface.[95,96] Sharing of load over different contact areas may decrease the prevalence of overuse injury in softball windmill pitching by not overloading the same structures during the course of a game or season. Investigation of inter-segment coordination may provide insights into the essential timing and sequencing of neuromuscular system control over biomechanical degrees of freedom, and the variability of coordination could reflect the adaptability of this control.

1.6 DEFINITION OF THE PROBLEM

Upper and lower extremity musculoskeletal injuries occur at a similar rate in softball pitchers.[2] Most of these injuries can be considered chronic in nature, which may result in symptoms being treated instead of considering the underlying mechanism for injury. Pitchers need to be taught proper mechanics from a young age to master the technique and minimize risk for injury. Sequential and well-coordinated force development throughout segments of the kinetic chain is essential to maximize force, while simultaneously minimizing internal loads at the joint. This sequential motion and position of the joints produces an interactive moment at the distal joint, allowing performers to use the already developed forces instead of having to create them.[65]

When this neuromuscular coordination breaks down, generation and transfer of force is diminished and compromised, softball pitchers may develop compensatory movement strategies that lead to overuse injury. Evaluating the sequence of linked movements used for a specific outcome may help identify compensations. However, previous research has focused on time-discrete variables obtained from isolated joint or segments in which a decision must be made beforehand as to which variables and time points the researcher believes will be important. This method fails to take into account motion at and interaction between proximal and distal joints and segments. Continuous methods of analysis have an advantage over discrete methods because they allow for examination of the data over the entire cycle rather than at discrete points. For example, the dynamical systems approach focuses on coordination of coupled segments or joints, emphasizing the relationship between segments rather than the individual parts. Using continuous methods unveils optimal, segmental and limb coordination for the body and the limbs to be moved in a specific sequence and time pattern. Through this, deviations in movement patterns can be found that can potentially lead to future injury or decrement in performance.

Much research has looked at baseball pitching mechanics, yet there is limited information on softball. Although softball and baseball are similar, there are several significant differences, especially in the pitcher position. This emphasizes the need to have softball specific research to look at coordination patterns, their stability and variability over consecutive pitches and whether it affects pitching outcomes. Corben et al. observed significant decrements in upper and lower extremity strength after pitching in a game.[97] However, there was no associated decrease in ball velocity. With a decrease in strength, the pitchers observed would have to use alternative mechanisms to maintain ball velocity. Research and live pitching performance shows that ball velocity can be maintained through consecutive innings. However, coordination patterns employed to achieve and maintain this velocity over the course of a single game have not been analyzed.

1.7 PURPOSE

The primary purpose of this dissertation was to examine inter-segmental and intra-limb coordination of Drive Leg Thigh flexion/extension v Pelvis axial rotation, Pelvis axial rotation v Thoracic axial rotation, Pelvis axial rotation v Pitching Arm Humerus flexion/extension and Pitching Arm Humerus flexion/extension v Forearm flexion/extension in the softball windmill pitch throughout a simulated game of softball to capture the stability or transitions in coordination due to consecutive pitches. The secondary purpose was to determine if variability of these coordination patterns change throughout multiple pitch counts, potentially due to muscular fatigue, that may result in maladaptive movement patterns. Additionally, the difference between pre-pitching and post-pitching concentric, isokinetic strength values were evaluated to determine if muscular fatigue, as defined by the inability to sustain the expected power output around a joint, has occurred.[98] Pitch performance, defined as ball velocity and accuracy, were measured throughout all pitches to determine if any outcome variability occurred.

1.8 SPECIFIC AIMS AND HYPOTHESES

Specific Aim 1: To establish coordination patterns of Drive Leg Thigh flexion/extension v Pelvis axial rotation, Pelvis axial rotation v Thoracic axial rotation, Pelvis axial rotation v Pitching Arm Humerus flexion/extension and Pitching Arm Humerus flexion/extension v Forearm flexion/extension during the windmill style pitch of softball pitchers at the start of a simulated game and last 5 pitches of every inning. To determine the most appropriate order parameter that encapsulates the windmill pitch.

Specific Aim 2: To examine variability of coordination patterns of Drive Leg Thigh flexion/extension v Pelvis axial rotation, Pelvis axial rotation v Thoracic axial rotation, Pelvis axial rotation v Pitching Arm Humerus flexion/extension and Pitching Arm Humerus flexion/extension v Forearm flexion/extension over a series of consecutive fastball pitches in a simulated game.

> Hypothesis 2: It was hypothesized that an increase of functional movement variability in Pelvis axial rotation v Pitching Arm Humerus flexion/extension and Pitching Arm Humerus flexion/extension v Forearm flexion/extension will manifest toward the end of the simulated game to maintain successful outcome.

Specific Aim 3: To compare concentric muscular strength of the knee, hip, trunk and elbow flexors and extensors and trunk rotators pre and post pitching of a simulated game.

Hypothesis 3: It was hypothesized that there would be a significant decrease in muscular strength, as percent of body weight, and time to peak torque of elbow flexors and extensors post-pitching of a simulated game compared to pre-pitching strength values.

Specific Aim 4: Assess pitching performance, as defined by pitch velocity and pitch accuracy, within the last 5 pitches of each inning throughout a simulated game.

Hypothesis 4a: It was hypothesized that both pitch velocity and accuracy would remain consistent throughout all innings of a simulated game.

1.9 STUDY SIGNIFICANCE

Despite the popularity of softball, there is still limited research on softball players. The identification of whole body coordination patterns during a softball windmill pitch will help to instruct pitchers on appropriate motor coordination. Previous research has demonstrated bilateral fatigue in upper and lower extremity musculature after pitching in a softball game, however ball velocity maintains relative consistency throughout a game.[97] Analysis of coordination throughout a simulated game will lend information on the ability of a softball pitcher to sustain ball velocity.

Recognizing the most appropriate order parameter in the windmill pitch will help narrow the focus of training for coaches. Manipulating constraints through coaching can facilitate the emergence of additional functional movement patterns. The use of additional movement patterns adds to the variability in coordination and may be an important etiological factor in decreasing softball pitching injuries. A more comprehensive understanding of the windmill pitching technique is need to design specific training and rehabilitation programs. Occurrence of or resistance to local muscular fatigue throughout a simulated softball game can help use appropriate training stresses to best prepare a pitcher to sustain performance.

2.0 REVIEW OF LITERATURE

This chapter will review previous literature that has examined the kinematics and kinetics of the softball windmill pitch to understand the basic biomechanics involved. The limited comprehensive research on softball will be addressed. Followed by muscular fatigue and its detrimental effect on neuromuscular control, movement and athletics will be discussed. The utilization and importance of linked, interdependent body segments, kinetic chain, will set a base of understanding whole body coordination of the softball windmill pitch. To appreciate the importance of coordination in injury prevention and performance optimization, an overview of dynamical systems will first be presented as a theoretical basis for this analysis. The previous use of coordination in movement analysis will be described. Effects of stability and variability in coordination will be presented as the premise for this specific research question.

2.1 EPIDEMIIOLOGY OF SOFTBALL INJURIES

Overuse injuries caused by the windmill pitching motion are prominent in softball pitchers but have not been extensively studied. In a 1989 study of pitchers who made it to the NCAA softball tournament, 20 of the 24 pitchers involved reported injury during that season, for a total of 26 injuries.[17] More recently, almost 73% of collegiate softball pitchers reported sustaining an injury over one season, with 31.7% experiencing more than one injury.[2] Out of the total injuries described in the survey, 61.1% were considered a direct cause from pitching.[2] Chronic upper extremity injuries have been attributed to the repetitive nature of windmill pitching, placing extreme forces on the shoulder and elbow.[17,18] Out of all injuries reported in one season by a sample of collegiate softball pitchers, 36 were classified as acute and 92 as overuse/chronic injuries. From those overuse injuries collected, 60 were associated with the upper extremity, 33 specifically involving the shoulder. Thirty of the total overuse injuries were associated with the trunk and lower extremity, 16 of those at the low back.[2]

Of those pitchers who sustained an injury during the 1989 season, there were fifteen grade I (non-time loss) injuries, with 13 being musculoskeletal. Additionally, four of the six injuries that were diagnoses as grade II (altered play) were musculoskeletal in nature.[17] Hill et al. used another classification system to help determine severity of overuse injuries reported by collegiate softball pitchers.[2] On their grading scale of chronic pitching injuries, observed injuries included:

- 10 grade I (pain after activity)
- 30 grade II (pain before and after activity without decreasing performance)
- 39 grade III (pain before, during and after activity that affects performance)
- 13 grade IV (intense pain that inhibits the athlete from playing)

Over half overuse injuries classified as grade II injuries were to the shoulder and low back and over one-third of grade III injuries occurred at the shoulder.[2] These studies document the high incidence and time loss of overuse injuries in collegiate softball pitchers.

As softball becomes more competitive at a younger age, there is a growing need to investigate injuries in an adolescent population. Smith et al. followed adolescent softball players for a single fast-pitch season; the majority of pitchers who incurred injury, which prohibited them from softball related activity, did so in the first 6 weeks of their season.[99] This may be evidence that poor conditioning might be a greater risk factor than cumulative fatigue in adolescent pitchers. Thirty-eight percent of the adolescent pitchers followed sustained an injury directly related to pitching, with 61% involving the shoulder.[99] Fifty percent of pitching injuries caused pitchers to miss at least two weeks of softball activity, with 17% missing more than 6 weeks and 22% suffering a season ending injury. Overall, pitching resulted in a higher risk of injury lasting more than 2 weeks as compared to field players.[99] Similarly, in another cohort of adolescent softball players, pitching was the most common mechanism of should injury that resulted in a time loss of greater than 9 days.[22]

In high school and collegiate pitchers, it has been reported that 64% have a history of upper extremity injury, resulting from throwing, that caused them to miss 1-9 days of activity.[100] More significantly, 20% of those pitchers have reported sustaining an upper extremity injury that prohibited them from pitching for more than 10 days. Among the time loss injuries recorded, 81% were sustained to the shoulder.[100] Time loss injuries to collegiate softball pitchers have been reported at 58% of all injuries occurred during one season.[2] With 82% of time loss injuries specifically involving the upper extremity.[17] Even with the high rate of injuries in softball pitchers, little has been documented on specific diagnosis, injury location or mechanism of injury in this population. It is important to understand the sequence of movements during the windmill pitch that produce the desired arm speed and direction at ball release.

2.2 MECHANICS OF THE SOFTBALL WINDMILL PITCH

Millions of people play slow-pitch softball recreationally worldwide; however, at the elite international level, fast-pitch softball is the dominant discipline.[101] Maffet et al. investigated the fast pitch softball windmill style delivery to describe the phases of the pitch.[24] They established phases of delivery based on the humerus' position in relation to the trunk in the sagittal plane, and labeled them as the positions of a clock (Figure 1).[24] The quantification of the windmill pitch allows for breakdown of motion into smaller phases, similar to the baseball pitch. However, this classification has also led the previous literature to describe movement throughout the windmill pitch only in terms of discrete time points. To best identify the structures at risk during the softball windmill pitch, an understanding of continuous movement is needed. Recognizing the movement patterns involved in the windmill pitch will also allow better diagnosis of injury and specific rehabilitation and conditioning programs.

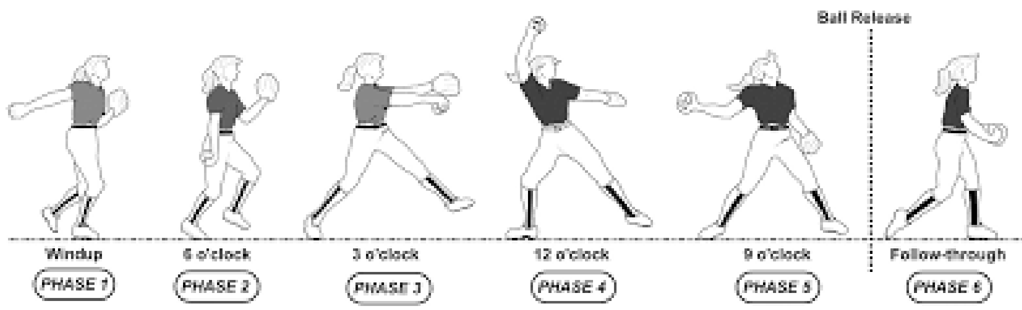


Figure 1. Phases of the softball windmill pitch

2.2.1 Kinetics and kinematics of the windmill pitch

The high performance demand of fast-pitch softball averages velocities at 55±3 mph (25±1 meter/second) for youth athletes[7] and 60±5mph (27±2 m/s) for Olympic pitchers.[9] Therefore, acceleration of the arm, to reach these high ball velocities of the windmill pitch, must occur rapidly. In a study of 53 youth softball pitchers, average time from the top of the backswing (approximately 12 o'clock position) to stride foot contact was 45±19 milliseconds and 117±17 milliseconds from stride foot contact to ball release.[7] Similar results were found observing softball pitching during the 1996 Olympics; with top of the backswing to stride foot contact being 50±16 milliseconds and 100±17 milliseconds from stride foot contact to ball release.[9]

Female athletes have a 4-6 times greater risk of non-contact knee injuries than male athletes.[102] However, there is a low degree of stride leg knee adduction during the softball windmill pitch.[28] This may contribute to the low number of knee injuries observed in softball pitchers.[2,17] In youth pitchers, stride length (measured as the distance from the ankle of the stance foot to the ankle of the stride foot in the forward direction) has been measured at 62% of subjects' height (103±10cm) with knee angle at initial stride foot contact measured at 33±8° shy of full extension.[7] A longer stride length was seen in Olympic pitchers, at 89±11% of height, with knee angle at initial stride foot contact measured at 27±9° shy of full extension.[9] Stride length has been reported to be 60-70% of the pitcher's height.[103] Stride leg hip adduction angles in competitive softball pitchers have been shown to be 38.96° at foot contact.[28] The positive adduction angle toward the opposing leg observed may be a result of decreased hip muscle activation and has been suggested to contribute to the low back pain experienced by pitchers.[17]

Total circumduction of the arm during the windmill pitch, from the initiation of stride phase to completion of the pitch, is about 485°.[18] At stride foot contact, pitching arm has been measured at 109±19° of shoulder abduction and 217±45° shoulder flexion in youths[7] and at 155±16° of shoulder abduction and 168±35° shoulder flexion in an Olympic population.[9] Throughout acceleration of the arm during the windmill pitch, the elbow stays in a relatively extended position. At ball release, the elbow flexes to 20±9° and the throwing arm is in 3±7° shoulder abduction and 5±7° shoulder flexion.[7] This keeps the ball release point close to the hip in the sagittal plane.

Upper and lower extremity momentum begins simultaneously with arm movement of the windup and weight shift. Weight is shifted to the drive leg and their trunk is rotated 90° toward third base (for right handed pitchers), which allows for greater trunk rotation as they stride forward during the windmill pitch, increasing the distance the ball has to accelerate before release.[104] To quickly transfer energy from the lower extremity to the arm, trunk rotational velocities are high during the delivery phase of the windmill pitch. Upper (shoulder girdle) and lower (pelvic girdle) trunk rotate at different speeds and in sequence. Lower trunk rotational velocity can reach speeds of 544±139°/s with the upper trunk peak rotational velocity reaching 901±162°/s in youth softball pitchers[7] and 616±165°/s and 779±191°/s, respectively, in Olympic pitchers.[9] Timing of trunk rotation is important for maximum velocity and to ensure direct alignment with the batter at ball release. If the hips do not rotate forward, the pitcher will lose momentum that can be produced by the powerful muscles of the trunk.[67] Momentum generated through the full rotation of the lower and upper trunk continues to transfer to the pitching arm. For softball pitchers to generate maximal ball velocity, rotational velocities of the arm during circumduction reach 1250±111°/s at the shoulder and 716±201°/s of elbow flexion in youth pitchers.[7] As the trunk rotates 90° back toward home plate, arm speed of Olympic pitchers has reached maximum shoulder angular velocity value of 2190±583°/s and elbow flexion velocity of 1248±431°/s just before ball release.[9]

High velocities of upper extremity movement require resistance to shoulder distraction while also controlling elbow extension. During the windmill pitch, to resist shoulder distraction, compressive forces have been recorded as high as 94±16% of body weight in youth pitchers[7] and 80±22% of body weight in Olympic pitchers.[9] To resist elbow distraction at ball release, compressive forces have been shown to reach 46±7% of body weight in youth pitchers[7] and

61±19% of body weight in Olympic pitchers.[9] The greatest resistance to distractive forces at the shoulder occur during acceleration and delivery in the windmill pitch, as opposed to the deceleration phase of the overhand baseball pitch. However, the magnitude of forces are similar. During the underhand windmill pitch, forces to resist distraction at the shoulder are 80-95% of normalized values for overhand pitching and 67-79% of normalized values at the elbow.[18] Proper mobility and stability throughout the windmill pitch is established through coordinated and synchronous muscle activation.[105]

2.2.2 Muscle activation patterns of the windmill pitch

Muscle activation patterns help understand how softball pitchers generate momentum and dynamically control body movement. Injuries are most likely when high forces and/or torques are repeatedly applied to vulnerable tissue.[13] The softball windmill pitch involves specific coordination of movement between the lower extremity, trunk and upper extremity to produce maximum ball velocity and accuracy. Drive leg hip strength is essential to initiate motion of the windmill pitch. From the windup to Phase 2 of the windmill pitch, body weight is transferred to the drive leg, making it the only contact the pitcher has to push off the ground. While a pitcher is only being supported by the drive leg, the hip musculature of that side must maintain pelvic stability. Highest gluteus medius and maximus muscle activation has been observed during the windup of the windmill pitch, when body weight is being shifted from the stride leg back to the drive leg, and during single leg stance at the beginning of Phase 2.[106]

Oliver et al.[106] examined muscle activation and described it in relation to phases of the windmill pitch. Gluteus maximus activation was seen to be highest during windup (196.3% maximum voluntary isometric contraction, MVIC) with the need to stabilize the pelvis. Second highest activity of the gluteus maximus occurs during Phase 4 (180.1% MVIC) as the drive leg pushes the body forward and stride leg contacts the ground.[106] Hip musculature is essential to help create a forceful drive back to a closed position (both hips facing home plate) allowing full contribution of the lower extremity into the pitch. During Phase 4, forward momentum is transferred from the drive leg to the stride leg and the gluteal muscles act to eccentrically slow forward progress. Gluteus medius is consistent over Phase 3 (101.2% MVIC) and Phase 4 (93.2% MVIC) as it stabilizes the pelvis and helps transfer momentum to the elevating humerus.[106] Upper extremity movement is likely dependent on the preceding lower extremity activation. Oliver et al.[28] found a positive relationship between ball velocities and drive leg gluteus maximus and gluteus medius muscle activity. This relationship likely due to the need of pelvic stabilization by hip musculature for efficient energy transfer to the upper extremity.

Shoulder girdle muscle activation have also been evaluated as the arm travels through phases of the windmill pitch. However, previous results only state which phase of the windmill pitch peak activity occurs in. The supraspinatus had the highest activity during Phase 2, 6 to 3 o'clock (78±36 MVIC) and then dropped to below 50% for the rest of the pitch cycle.[24] This activation pattern likely to maintain the humeral head centrally in the glenoid fossa and prevent superior translation. Anterior deltoid was most active during forward movement of the humerus in the sagittal plane but was the least active muscle of all recorded. Highest muscular activity of the anterior deltoid has been recorded during Phase 5 (43±38% MVIC) and Phase 2 (38±29% MVIC).[24] Scapular stabilizer muscle activation is important during arm elevation to rotate the scapula, allowing space under the acromion for function of the rotator cuff musculature.[107] The rhomboids have the highest muscle activation during Phase 2 (170.1% MVIC) in an attempt to stabilize the scapula as the arm is forward flexed.[106] The infraspinatus recorded its highest activation during Phase 2 (93±52% MVIC) and Phase 3 (92±38% MVIC).[24] These phases correspond with shoulder flexion while the arm moves from internal to external rotation. In Phase 3, the posterior deltoid had the most activity (102±42% MVIC) in addition to the teres minor (87±21% MVIC).[24] These muscles work together to externally rotate the arm as it elevates toward the 12 o'clock position. Moving from Phase 3 to Phase 4, the pitching arm is at the highest point of circumduction and the trunk is rotated 90°. For a softball pitcher to rapidly externally rotate her pitching arm at the point of full flexion requires the shoulder girdle to recruit muscle activity.[24] Biceps brachii had the greatest activation with the elbow extended during Phase 4 (100.9% MVIC) and second highest during Phase 5 (73.2% MVIC) as the arm begins to decelerate.[106] The pectoralis major, subscapularis and serratus anterior all had highest muscle activation during the end of the windmill delivery, as the arm is internally rotated and adducting across the body. During Phase 4, the pectoralis major reached 63±23% MVIC, subscapularis 81±52% MVIC and serratus anterior 45±39% MVIC. In the final phase of the windmill pitch, maximal pectoralis major activation was reached (76±24% MMT) as the arm is further adducted across the body, with activation levels of the subscapularis at 75±36% MVIC and serratus anterior at 61±19% MVIC.[24] The pectoralis major and serratus anterior appear to work in synchrony, attempting to stabilize the scapula against acceleration forces of the pectoralis major acting on the humerus. Triceps activation was greater than 150% MVIC throughout all phases of the windmill pitch.[106] Most shoulder girdle muscle activity decreased after ball release, as energy dissipates during arm contact with the lateral thigh, which lessens the eccentric demand on posterior musculature to slow arm. None of these studies examined muscle activation ratios to determine if there was an optimal muscular balance that may change throughout a game, season or due to injury. A softball pitcher's velocity, consistency and durability may be linked to kinematic and kinetic factors as well as the temporal association of segmental body motions; which begin with proper transfer of ground reaction forces.

2.3 RISK FACTORS OF SOFTBALL PITCHING INJURIES

The assessment of risk in sport is of interest for athletes, clinicians and coaches alike. There has been an emphasis on measuring joint mobility, muscle flexibility, endurance, strength and other physiological tests,[108,109] but currently the strongest predictor of future injury is previous injury.[110,111] However, attention has now been focusing on non-symptomatic deficits of movement patterns that may predispose a person to injury.[112,113] The repetitive nature of softball windmill pitching can put athletes at greater risk of overuse injuries. Overuse injury due to repetitive movement can be described as a ‘cascade to overload injury’ in which the cycle towards an injury begins with a minor adaptation in terms of strength, flexibility and biomechanics, causing an alteration to the movement pattern.[114] Initial musculoskeletal maladaptation to repetitive movement become more pronounced, pushing the athlete toward overt injury.[114]

Other risk of injury have been attributed to surrounding musculature that contributes to movement patterns.[115] Motor control deficiencies in local stability muscles, which control inter-segmental movement, have been linked to pain and recurrence of injury.[116,117] These proximal trunk and pelvis muscles are important during the windmill pitch for energy transfer from the lower extremity to the upper extremity, although they are never assessed prior to injury.[118] Trunk and pelvis muscular activity occurs before the extremities to provide a foundation for functional movement.[119] Increased stride leg hip adduction angles seen in softball pitchers have been thought to be a result of decreased hip muscle activation and increased activation on the contralateral side.[28] This increase in hip adduction and external rotation can increase the compressive forces at the lumbar vertebrae, increasing the incidence of low back pain in softball pitchers.[17] Although this hip adduction of the stride leg may also be compensatory for current low back pain. It has been shown that muscle recruitment and motor control impairment may result from previous injury,[120] fatigue or muscle imbalance.[112,113] Alterations in hip movement of softball pitchers may lead to future injury or be perpetuating the cycle from previous injury.

Imbalance between stability and muscular mobility can present in alterations in functional length and recruitment of muscles, resulting in abnormal forces on a segment in motion. In pitching, the lower extremity and trunk generate energy to be transferred through the upper extremity and directed to ball release. This sequential activation requires significant coordination. Activation of the gluteal muscles helps to stabilize the pelvis and the power generated can be transferred to the upper extremity, rather than having to be generated in the upper extremity.[115] Without a proper base of support, direction specific mechanical stress is placed on distal structures (such as the biceps), that when overloaded, can result in pain and pathology.[121] In the throwing athlete, the long head of the biceps is one of several muscles that helps to position the shoulder and elbow.[122] During the windmill pitch, the biceps assists with compressive force to the humerus during high magnitude of shoulder distraction.[18] During early acceleration, the eccentric contraction of the biceps brachii helps to control elbow extension.[123] This eccentric contraction occurs during the 9 o'clock position of the humerus, as the arm is beginning to decelerate and the elbow is in maximum extension. Highest values of biceps muscle activity has been recorded during these times of peak shoulder distraction stress and elbow extension torque just prior to ball release.[7,18,124] The biceps must also actively control the forearm motion at the end of the pitch cycle. During ball release, the stress placed on the biceps increases as it first controls elbow extension and then produces elbow flexion.[124] The inability to control movement at either the shoulder or elbow may increase stresses on the biceps, increasing susceptibility to injury.[120] Maximum biceps activity has been shown to be higher in softball pitchers (38±16% MMT) as compared to overhead baseball pitchers (19±11% MMT).[124] This difference in muscle activation is likely because of the increased eccentric contraction of the biceps during arm deceleration and with maximum elbow extension during the softball windmill pitch.

If injury to the low back or biceps occurs in a softball pitcher, new movement patterns may develop due to pain or loss in strength. Compensatory movement of a segment has been frequently observed with a loss of range of motion or decreased strength at an adjacent segment. During whole body movement, a stiff or painful segment will resist motion but function is maintained due to compensatory movement at an adjacent segment.[125] Also needed for controlled movement is the ability to activate muscles to control one segment while producing movement at another.[125] A weakened muscle, due to injury or fatigue, will disrupt normal movement patterns but will be compensated by an altered pattern by a muscle capable of achieving similar motion.[126] Pain or fatigue often leads an individual to compensate with available movement strategies.[127] It is unclear as to whether fatigue decreases range of motion and speed of movement, decreasing joint loads, or if it occurs in an attempt to decrease potential of injury.[33] These inadvertent variations in a movement parameter are counteracted by actions of other parameters, to manage previous error and prevent negative influence on task outcome.[88] A thorough knowledge of the changes that occur as the number of pitches increases provides valuable information regarding how long a pitcher can throw before mechanical breakdowns start to happen which can eventually lead to performance decrements and the potential for injury.

2.4 FATIGUE EFFECT ON PERFORMANCE

As softball has become more popular, it has turned into a year-round sport with players participating in multiple teams and tournaments. This high volume of repetitive activity allows little time for rest and recovery, putting athletes at a greater risk for overuse injury.[7] While pitch counts have long been established for baseball, there are still no regulation as to how much softball pitchers can throw. Fatigue is often identified as a risk factor for musculoskeletal injury because it can influence strength, proprioception, neuromuscular control and biomechanics.[128,129] Yet many neurophysiological mechanisms are altered before an athlete even begins to feel the effects of fatigue.[130] Fatigue develops progressively until the muscle is no longer able to perform the required task, leaving the muscle susceptible to injury. Stretch induced muscle injuries, or muscle strains, are a common injury in athletics. Mair et al.[131] investigated the effect of fatigue on acute muscle strain injuries, finding that the more the muscle was fatigued, the less it was able to absorb energy. The decreased ability to absorb energy may also be related to the reduced contractile strength of fatigued muscles. Fatigued muscles therefore place greater stress on joint articulations and static structures.[56]

Energy transferred from the lower extremity to the upper extremity must be properly controlled to effectively disperse such forces.[132] Fatigue has been shown to disrupt sensorimotor function resulting in the inability to maintain correct mechanics throughout repetitive motions.[33] A fatigued system can impede neuromuscular control and lead to functional instability.

Neuromuscular control is defined as unconscious activation of dynamic restraints in preparation for joint motion and loading to maintain functional joint stability.[133] Neuromuscular adaptations due to fatigue can interfere with coordination and muscle synergies needed for complex movements. Fatigue can cause decreased neuromuscular control and proprioception creating two potential mechanisms for injury. Feedback integrated at the central nervous system causes neuromuscular responses as both spinal reflexes and preprogrammed responses that maintain functional stability.[36] Fatigue disrupts this feedback from the joint to the central nervous system, which may lead to joint instability. Second, the inability to recognize joint position sense due to fatigue can increase the mechanical stress of joints by allowing them to move into vulnerable positions.[134]

Fatigue's effect on neuromuscular control has been studied through its influence on postural control. Decreased postural control has been shown after fatiguing exercises is thought to be a result of altered somatosensory input reducing neuromuscular control.[42,43] Altered motor control strategies have also been found after muscular fatigue as male and female athletes demonstrate increased peak proximal shear forces, valgus moments and decreased knee flexion angles during landing of three separate stop-jump tasks when fatigued.[44] Following a functional agility fatigue protocol, female athletes showed increased knee external rotation and decreased knee and hip flexion angles during a stop-jump.[45] It has been suggested that fatigue's influence on multiple characteristics necessary for dynamic activity contributes to the large number of non-contact anterior cruciate ligament (ACL) injuries.[46-48]

Muscle fatigue is seen as an exercise-induced reduction in the capability of a muscle to generate force.[135] In a continuous multi-segmental movement, such as hopping, activity is able to be sustained for long durations of time, but using two different strategies (earlier preactivation and trade-offs between muscles across different joint levels).[61] Change in strategy may be as compensation for the loss of force generating properties in lower extremity musculature due to fatigue. Similar results were seen in a repetitive sawing task; significant changes in biomechanics lead to greater variability in a fatigued state. However, this altered coordination did not lead to greater instability.[136] Rodacki et al.[137] found different results investigating the segmental coordination of a countermovement jump under fatigue. A decrease in jump height was found but no change in motion strategies due to fatigue. They stated that subjects used a 'robust pattern' that may be guided by a fixed set of neural commands to agonist-antagonist muscle groups. This notion is supported by previous research examining if fatigue influences lower-dimensional motor control organization and coordination at the neural level. It was found that muscle synergies remain stable through the onset of fatigue, possibly because movement strategies are at the neural level instead of muscular.[138]

In collegiate pitchers, fatigue has been shown to decrease overall endpoint acuity as well as the ability to replicate an arm cocked position and ball release position.[139] Performance demands of softball pitchers has been assessed by recording upper and lower extremity fatigue patterns associated with a real-game fast-pitch performance. Corben et al.[97] looked at bilateral muscular fatigue before and after pitching a softball game (99±21 pitches). They found bilateral differences in the large hip and scapular stabilizer muscles. They found bilateral significant decreases in strength for hip flexion and extension, hip abduction and adduction, middle and lower trapezius and rhomboids. Significant decrements of strength were also found bilaterally in shoulder: flexion, abduction, adduction, internal rotation, external rotation and the empty can test. Bilateral elbow and wrist flexors, and supinators had significant differences post game, as did pitching arm supinators. Their results show a clear pattern of muscular fatigue through the kinetic chain.

At risk from fatigue during pitching is the shoulder. The glenohumeral joint's bony anatomy does not provide much stability, forcing the muscular anatomy to provide dynamic stability. When these muscles become fatigued, altered mechanics may result creating the potential for shoulder pathologies. Fatigued shoulder musculature has been shown to result in altered scapulothoracic and glenohumeral kinematics. Following muscular fatigue, Ebaugh et al.[140] observed less humeral external rotation, less posterior tilt of the scapula at the beginning of arm elevation and increased scapular upward rotation during midrange of elevation. McQuade et al.[141] found that shoulder fatigue directly related to the way the scapula moves concomitantly with the humerus. Fatigue resulted in increased scapular rotation in the midrange to end of arm elevation, altering scapulohumeral rhythm.[141]

Research of fatigue's effect on pitchers' mechanics has only been reported in a baseball population. Seven major league baseball pitchers were recorded throughout a game where much of the parameters significantly changed between the first and last inning pitched. These included decreases in maximum external rotation of the shoulder, knee angle at ball release, decreases in maximum distraction forces at the shoulder and elbow joints and horizontal abduction torque at ball release and peak amplitude. Significant decreases in ball velocity were also seen between the first and last innings pitched.[33] In Division I collegiate baseball pitchers, innings that lasted more than 15 pitches showed changes in pitching mechanics as compared to the start of the inning. Variability, as defined by the standard deviation of each parameter, was seen between first pitch of the inning and 16th pitch for stride length at foot contact and stride knee flexion and shoulder alignment at maximum external rotation.[35] Mechanics of the first inning to last inning pitched were also significantly different for maximum shoulder external and glove height at ball release and follow through. Decreased variability was seen for knee flexion at balance point, hip lean as the hands separate, and elbow flexion and glove height at ball release with increasing variance for maximum shoulder external rotation.[35] Escamilla et al.[56] also looked at collegiate baseball pitchers and the effect of fatigue on pitching mechanics. Pitchers threw fifteen pitches per simulated inning until they felt they could no longer continue due to subjective fatigue. Compared with the initial two innings pitched, the last two innings showed a significant decrease in ball velocity and trunk position significantly closer to a vertical position.[56] Decrease in trunk tilt may inhibit effective transfer of momentum from the lower extremity, slowing arm acceleration and resulting in a decreased ball velocity. Erickson et al.[34] observed adolescent baseball pitchers' mechanics over a simulated game. Pitchers remained accurate over multiple pitch counts but showed a significant decrease in ball velocity (73±5mph to 71±6mph).[34] Upper extremity kinematics remained unchanged throughout the 90 pitches thrown, while knee flexion at ball release increased and hip-to-shoulder separation decreased.[34] This may suggest that in adolescent baseball pitchers, lower extremity and core musculature fatigue before upper extremity musculature.

Mullaney et al.[52] tried to quantify this fatigue associated with continuous pitching; 13 collegiate baseball pitchers studied threw an average of 99 pitches each game. A handheld dynamometer was used to assess strength of the shoulder, scapular stabilizers and lower extremity musculature before and after games pitched. Significant decreases in postgame strength were seen in shoulder flexion, internal rotation and adduction.[52]

Consecutive pitching has also been linked to injury. Lyman et al.[12] found a relationship between number of pitches thrown and shoulder or elbow pain in youth pitchers, with a 6%

increase in the odds of elbow pain when more than 10 pitches per game were thrown. When over 75 pitches were thrown per game, the odds of experiencing elbow pain increased to 50% and pitchers were 3.2 times more likely to have shoulder pain.[12]

The process of fatigue is gradual and includes important physiological changes that occur before and during the mechanical failure.[142] Effects of fatigue have been evaluated by discrete kinematics of sport specific motions as a result of changes in temporal muscle activation. A possible strategy has to counteract the effects of fatigue has been proposed as modifying muscle coordination, defined as a distribution of muscle activation or force among individual muscles to produce a given combination of joint moments.[143,144] Muscle synergies represent the global temporal and spatial organization of the motor output and provide a simplified strategy for the control of complex movements because they reduce the number of output patterns that the nervous system must specify for a large number of muscles.[145,146] Movement patterns may be modulated if muscular fatigue begins to set it during activity. Fatigue can be highly detrimental, as the musculature must work harder to make up for lost energy, farther accelerating fatigue and compromising overall performance.

2.5 KINETIC CHAIN

Strength and conditioning of softball pitchers often focuses on the upper extremity only; however, the driving force of the windmill pitch is not the shoulder.[28] Coordination of linked, interdependent body segments work in a proximal to distal sequence to generate, summate and transfer force to the terminal link (the hand in softball pitchers) if often referred to as the kinetic chain.[147] Proximal segments accelerate the body and sequentially transfer momentum to the next segment. Summation of segmental speeds has been observed in throwing, where the end goal is to reach maximal ball velocity.[148] The kinetic chain model illustrates contribution of the entire body during activity, rather than individual segments.[65] In the softball windmill pitch, there is a certain uniformity observed throughout the entire motion.[149]

Proximal to distal sequencing is seen in the softball windmill pitch starting with the lower extremity and pelvis and moving to the upper torso and ending with the arm. The goal of this motion is to generate the greatest force on the distal segment. To achieve this, sequencing of segmental movements creates a lag which allows the proximal segment to reach a high angular velocity before initiation of the distal segment.[41] This lag elongates the muscles, permitting greater force production through storage of elastic energy and the stretch-shortening cycle.[69] The greatest amount of kinetic energy is initiated in the larger, proximal segments. Studies have shown in some overhead athletes, 51% of total kinetic energy and 54% of total force are developed in the legs and trunk.[64] Optimal timing and strength throughout this process is essential for the effective transfer of energy, as each movement sequence builds upon the previous motion. Alteration, or disruption, to one segmental movement along the kinetic chain can cause a loss of energy transfer. Consequently, the contribution of subsequent joints must increase to accommodate the loss, therefore these segments experience amplified loading, if overall performance is to be maintained. Kibler has shown that a 20% decrease in kinetic energy from the hip and trunk leads to a 34% increase in rotational velocity at the shoulder to maintain ball velocity.[147]

Sequential timing of energy transfer is a skill that is learned over time, as seen by timing differences in baseball pitchers of different skill levels.[70,122] Aguinaldo et al.[150] found that professional baseball pitchers generated less normalized shoulder internal rotation torque than less experiences pitchers; concluding that professional pitchers were able to maximize efficiency by rotating their upper trunk with specific timing to allow energy to pass from the trunk to the shoulder in appropriate sequence. Improper trunk rotation in less experienced pitchers has been shown to require them to generate larger amount of energy in their shoulder, rather than allowing it to amplify as it traveled up the kinetic chain.[151] Flesig et al.[152] also found differences in rotational timing between the pelvis and upper trunk of youth and high school baseball pitchers as compared to college and professional pitchers. Similar results have been seen in softball pitchers. Oliver et al.[153] observed joint motions and movement patterns of the softball windmill pitch between females of different skill level, assessing the relationship between the trunk and upper arm, upper arm and forearm, forearm and hand by looking at the percent of shared positive contribution (SPC) of adjacent segments. It was observed that the novice (< 1 year softball pitching experience) group did not display proximal to distal sequencing.[153] The novice group's percent contribution displayed the inability to accelerate each segment so the succeeding segment lags behind, limiting the final segmental maximal speed.[153]

Kinetic chain deficits of the lower extremity, trunk and scapula have been seen in 50-67% of athletes with shoulder injury.[154] The final velocity of the most distal segment depend on the proximal segment and its ability to accelerate momentum through consecutive segments. The ability to generate and transfer energy from larger, proximal muscles to smaller, distal muscles is imperative for injury prevention and performance optimization.

2.6 COORDINATION OF MOVEMENT

Initial acquisition of overhead throwing is a skill that is progressive, advancing from a single movement to a sequence of movements utilizing the body as a kinetic chain.[155,156] Traditional theories of human movement are based on the division of components and their isolated functions, training only microscopic parameters.[72] Multijoint movement is complex, kinesiological data must be analyzed and interpreted in the context it occurs.[157] The interdependency of movements supports the achievement of a behavioral task termed coordination. Coordination can be broadly defined as the patterning of the body and limb motions relative to the patterning of environmental objects and events.[74] The complexity of determining how movement patterns are learned is referred to as the degrees of freedom problem. If the body is viewed as only mechanical joints, there are about one hundred degrees of freedom, each quantified by position and velocity.[74] An individual has more available degrees of freedom than is actually needed to complete any given task. Nikolai Bernstein expressed this explaining that the fundamental problem of a movement systems is "the process of mastering the redundant degrees of freedom… the organization of the control of the motor apparatus".[79] Redundant degrees of freedom (DOF) are referred to as excessive degrees of freedom over what is required to accomplish a movement pattern.[158]

From a neuromuscular approach, movements are composed of muscle contractile strategies derived from a limited set of distinct contractile patterns. These limited patterns are a result of neural organization limiting the number of combinations of muscle contractions and associated movement trajectories.[159] However, a large number of muscular, skeletal and neural components are involved in the coordination of biological movements. These neuromuscular and biomechanical components determine the degrees of freedom available for movement. The information processing perspective on motor skill learning has been associated with the process by which one attaches meaning to information, mainly perception.[160] This theory states that sensory modalities (such as visual, auditory, tactile) provide input to the brain where information is interpreted, leading to a specific response pattern.[161] When the number of states of each component is taken into account within the information processing theory, there becomes too many degrees of freedom in any given movement to make executive control by the brain possible.[79] Therefore, the basic problem of coordination is mastering the multiple degrees of freedom by reducing the variables to be controlled. One theoretical framework on how coordinated movement is controlled is dynamical system theory which states that there is an integration of small systems (e.g. biological, muscular, skeletal, neurological) cooperatively functioning together to meet the environmental demands.

2.6.1 Dynamical Systems

Dynamical systems are defined by the notion that system states evolve over time. Although many systems in science are nonlinear in nature, they have traditionally been analyzed in a linear fashion. In linear dynamics, behavior is always proportional to its causes, while nonlinear systems demonstrate proportional and non-proportional changes. For example, in nonlinear dynamics a small change in the system (micro) may produce large changes in the system's behavior (macroscopic).[162] Another difference between classifications is that in linear systems, a single cause can only generate one behavior effect and nonlinear systems are considered multi-stable.[163] The difference in effects can be observed through parametric control, where by changing specific parameters one can guide the system to explore different organizational states. The final major characteristic difference is that 'noise' has often been viewed as undesirable and produces undesired system variability within a linear system.[80] Nonlinear systems interpret variations as the capability to make flexible adaptations to the surrounding environment.[164]

The fundamental principle of dynamic systems theory is that individual's change over time is not necessarily smooth and hierarchical.[160] Movement patterns emerge from the interaction of constraints between and within the elements of the system.[165] Dynamical systems affords a clear distinction between the system producing a specific behavior and the behavior itself. Motor learning is viewed as nonlinear and seen a discontinuous process. The ability of an individual to change over time is not necessarily smooth and hierarchical, and does not always move toward higher levels of complexity and competence in the motor system.[160]

The degrees of freedom available are usually larger than expressed in a behavior.[166] All possible states of coordination into which the system's degrees of freedom allow, coordination potential of a movement system, is referred to as the state space.[167] As opposed to biomechanics, dynamical systems studies mechanical degrees of freedom in addition to non-mechanical degrees of freedom variables such as information, coordination, fatigue and practice level; these variables describe the state space of a system.[168]

The redundancy in DOF allows for multiple strategies to accomplish any given task, providing flexibility to adapt to perturbations. The two main concepts from Bernstein states that different degrees of freedom can be used to achieve the same outcome and that the same degrees of freedom can be used for different movement outcomes.[95] Movement systems manage with redundant DOF through temporary couplings of multiple DOF called coordinative structures.[74] It has been proposed that coordinative structures are organized in a flexible or task specific manner, on the basis of inherent dynamical resources provided by the neuromuscular system.[169] These coordinative structures temporarily utilize natural connections of the anatomical system (muscle-joint linkages) to reduce the complexity of movement. By using the inherent interconnectedness of the human anatomy, these physical constraints decrease the large number of DOF that need to be regulated. With a reduced number of DOF, development of functionally preferred coordination, or attractor states, are developed.[170] An attractor is a preferred state that a system gravitates to from start or after a disturbance in the system.[74 168] Attractor states are are highly ordered and stable, leading to consistent movement patterns for specific tasks. Identifying attractors is important in understanding how stable patterns emerge, are maintained and how they become unstable.[171] Movement dynamics are attracted toward the task goal through construction of new, stable spatial and temporal properties that reflect a new attractor. Bernstein's perspective explains that it is not the parts themselves that are important to movement but the relationship of how those parts act together.[79] The emphasis on the relationship of segments stems from the idea that there are many combinations all of these parts can act together to produce the same movement.

Rhythmic movement is seen as the cornerstone of a theory of coordination, because coordinated activities are essentially patterns evolving sequentially in time and are the sum of periodic contributions.[74] Perturbation to the system results in brief alteration of oscillation but is quickly followed to its original behavior, or attractor state.[172] A limit cycle is a nonlinear oscillating system that remains relatively stable despite small perturbations.[172] A graphical examination of this movement can be observed plotting an oscillator by its velocity at each point of its cycle on a phase portrait.[173] Rhythmic movement does not produce a single orbit in the phase portrait, but successive cycles of nonidentical movement.[74] Undetectable alterations in movement patterns decreases the risk of overuse injury and allows the individual to explore multiple movement options for one consistent outcome. A softball pitcher's arm travels in a smooth circular pattern for every pitch. However, slight adjustments in coordination must be made to not overstress soft tissue, to compensate for potential fatigue or to adjust ball release to a new batter. Patterns of coordination can be thought of as temporarily assembled structures due to the successful cooperation of multiple underlying subsystems.[174]

In a coordinative state, subsystems must behave in a highly cooperative manner without relinquishing their distinctive individual qualities. Von Holst categorized coordination in the neural and rhythmic activities of animals and humans; finding the most common coordination pattern is absolute coordination, where two or more segments move rhythmically together at the same 1:1 frequency.[74] Von Holst presented this model in his research of rhythmic interfin movements of a fish. Each oscillator (fin) has its own preferred frequency dictated by its defining qualities, but when swimming would move at the same frequency.[175] Competition between oscillators to remain at their own frequency, satisfying its intrinsic dynamics, is referred to by von Holst as the maintenance tendency. Each oscillator tries to pull the other into its frequency, but both end up between the preferred frequencies of each. This is opposed to the magnet effect of absolute coordination, where one oscillator dominates the other.[74] Relative coordination between individual fins is thought to be a combination of the maintenance tendency and magnet effect; where segments are neither completely independent nor linked in a fixed relationship. Von Holst demonstrated how complex systems can work together, to reduce the DOF the need to be controlled, yet maintain independence to still allow for flexibility to reorganize into a new pattern of coordination.

How one utilizes a subset of near infinite DOF is key to understanding motor control. Coordination is a function of temporarily assembled structures with multiple underlying subsystems.[176] In a coordinated state, these subsystems are able to behave in a highly cooperative manner without losing their unique individual qualities. Self-organization theories have recently been used to understand complex behavior in various fields of science, such as physics and biology.[177] Theories in science help explain those systems composed of a large number of elements, whose non-linear interactions create a stable form in time and space. Self-organization refers to the spontaneous formation of patterns and pattern change within an open system, composed of very many components, that is open to the exchange of matter, energy and information with its surroundings.[178] Stable patterns of relationships are distinctive in skilled, cyclical performance and critical to self-organization. These stable patterns may be reorganized through control parameters, which act as an agent for reorganization of the motor pattern but do not dictate when change will occur.[179] Control parameters can be thought of constraints surrounding the motor system. Physical training within this model should encourage self-organization in an integrated, overall way, changing the environment and conditions to constrain an athlete in the desired direction of the training process. As the control parameter is increased, the dynamics within the order parameter become unstable, leading to the adoption of a new attractor state.[180] Non-linear dynamics are encapsulated by an order parameter, which is an expression of cooperation between individual components within this complex system.[177,181]

Kelso used the concept of synergies (coordinative structures) of dynamical systems to account for self-organized behavior both at the cooperative, coordinative level and at the level of the individual coordinating elements.[182] In his work on bimanual coordination, Kelso asked participants to oscillate their index fingers at a common frequency. He found only two spontaneously formed coordination patters: in-phase and anti-phase, which correspond to synchronous co-planar motion of the fingers in the same or opposite direction, respectively.[183] In this case, in-phase correcponds to 0° or relative phase and anti-phase to 180°. In coupled oscillator dynamics, the variable (order parameter) to capture coordination between oscillating fingers was phase lag, or relative phase.[184] Relative phase measurements determine the interaction of two oscillating objects' position within their cycles and sets them into relation: the relative-phase is the difference of the objects' position in their cycles.[185] Relative phase constituted the order parameter because it characterized the coordinative modes and changed abruptly at the transition.[77] Change in control parameter characteristics, after a critical value, result in change in the behavior of the order parameter.[186] As the frequency of finger oscillation increased by instruction (control parameter), the anti-phase became difficult to maintain that at a critical frequency it switched into an in-phase pattern.[183] These coordination patterns represent stable states or attractors of the bimanual system dynamics, since the pattern adopted initially, or if perturbation is applied to the ongoing finger movements, coordination eventually returns to one of these two modes.[184] Segments of intra-personal coordination are coupled through the central nervous system and act in a coordinated manner on the basis of common, shared information.[185] Similar to changing the speed of finger oscillations, muscular fatigue may be a strong enough control parameter to switch coordination patterns after multiple consecutive pitches.

The ability to develop a stable movement pattern often takes time and learning. Beginners, attempting to control the many degrees of freedom, typically display a rigid movement essentially eliminating some degrees of freedom. As skill progresses, one releases these degrees of freedom to open more functional units of movement.[187] Bernstein outlined this three stage model of motor learning: 1) reducing the number of degrees of freedom at the periphery to a minimum, 2) gradual releasing of all restrictions to incorporate coordination of all possible degrees of freedom, and 3) exploiting the reactive phenomena that arise in movement control.[79] In early learning, multiple dynamical variables are not organized, resulting in a degree of randomness that appears as "clumsy" behavior. This type of behavior may be thought of as noisy because the pattern used for a first attempt at movement has either completely changed or has been significantly altered in the following attempt. Early learners are still establishing a relationship between motor system components and movement. In Bernstein's view, practice allows for learning to control the forces of one body segment influencing another body segment.[188] In athletics, it has been suggested that during this stage the interactions between coach and athlete are minimized to allow discovery of control variables instead of relying on specific instruction.[83] Novices tend to use sources of information that may only be partially functional in certain performance conditions because they do not specify actions effectively.[189] As skill is learned, individuals become more attuned to higher order derivatives of movement displacement information such as velocity and acceleration.[190] This is followed by reducing, standardizing and stabilizing the dynamical variables that generate a coordination pattern and then become ordered by it, making movement appear less random.[191] A decline in variability as skill increases corresponds with a decline in the number of active DOF at the subsystem level. The final stage of motor learning, according to Bernstein, requires less expenditure of active force as an individual learns to exploit the passive forces from the interactions of body segments.[188] Expert behavior is illustrated by stable movement patterns that are consistent over time, resistant to perturbations and reproducible under different task and environmental constraints. Expertise is often associated with the ability to function through multiple motor solutions, exploiting system multi-stability .[189]

The number of active DOF of motor output may not always be reduced with practice and learning.[188] Coordinative systems are organized in a flexible manner based on inherent and incidental dynamics.[169] Optimal patterns are achieved through the continuous interactions of biological movement systems and its environment; internal and external constraints.[81,192] These constraints serve only to channel and guide dynamics; it is not that actions are caused by constraints.[180] Newell categorized the source of performance constraints into organismic, environmental and task (Figure 2).[81]

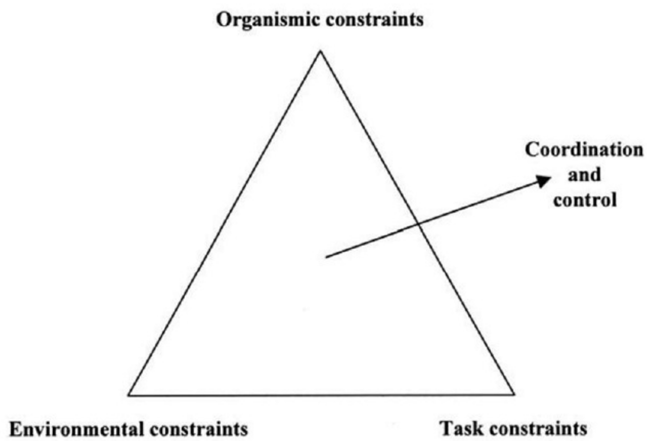


Figure 2. Interaction of constraints on coordination

Organismic constraints are founded within an individual's neuromuscular system. These can be subdivided into structural and functional constraints. Structural organismic constraints are physical constraints that remain relatively constant over time; such as gender, height, body mass, anthropometric characteristics, muscle fiber composition, range of motion in articulating structures and resistance to fatigue.[193] Functional organismic constraints can change considerably over time and can be physical or psychological; such as heart rate, lactate concentration, anxiety, level of expertise, emotions, perception, and memory.[180] Intentions of the individual appear to be the most influential in shaping coordination.[172] These person-related factors provide affordances (possibilities) for action and play a significant role in determining coordination patterns adopted by the individual.[194] For example, a taller basketball player may play closer to the net and take shorter shots while a shorter player plays at the perimeter and relies on taking 3 point shots. Environmental constraints are external to the individual and can refer to the physical or socio-cultural factors that movement occurs in and cannot be manipulated.[194] Ambient conditions (light, temperature, gravitational forces) the role of social context, such as peer groups and cultural expectations can influence coordination.[81] Environmental constraints are spatial and temporal constraints stemming from the surrounding world that continuously act on the neuromuscular system. Task constraints pertain to the goal of the activity and specific constraints imposed, such as rules, instructions or use of instruments.[81] In contrast to other constraints, task constraints can be easily maniplulated to an extent; such as modifying equipment of changing boundaries or goals. These categories only identify the source, not the nature, of constraints acting on performance and need to be considered by the perspective of the individual.[195]

Some constraints may be more influential than others in specific performance contexts, it is the convergence of interacting constraints that shape coordination.[196] Explosive power output is required within a multitude of sports, easily leading to muscular fatigue that may effect coordination patterns. The potential for reorganization of multi-segmental coordination after fatigue has been evaluated in vertical jumps. A decline in maximal jump height was observed without a significant change in coordination patterns. [63,137] However, in an overhead throw, decrease in successful throws and an absence of a temporal delay between the elbow and hand was seen with fatigue.[57] Increased rigidity likely simplified multijoint movement execution and control. Muscular fatigue is transient and highly fluctuating, creating a need for systems to be adaptable enough to predict a wide range of motor situations. Constraints placed on an individuals dynamical movment system changes continously, therefore optimal patterns of coordination can change accordingly.

Although stable movement patterns are essential to skilled performance, perfect coordination cannot be maintained and variability can be both inevitable and desirable.[74] Unlike traditional methods of physical training, in dynamical systems the athlete does not need to know the solution of the task beforehand. A complex interaction between the components participating in the motor By manipulating these constraints and increasing the amount of variability, one can find new solutions to a specific task goal. Change in coordination patterns are due to internal and external constraints that pressure system components to change.[88] An ideal technique will exist for each situation and for each individual. For this reason, it is necessary to physically train athletes to adapt to change instead of copying an external solution.[72] Adaptability allows for motor behavior to fit performance circumstances.

Extensive research has looked into motor learning of rhythmical movement such as swimming, but little work has been done on coordination patterns of discrete movements. Anderson and Sidaway examined changes in coordination with practice of the soccer kick, and compared that to movement patterns of a skilled player. After a practice phase, learners improved segmental sequencing to a level that was almost comproable to skilled players. However, they were unable to appropriately scale significant movement parameters, such as linear velocity of the foot.[197] Chow et al.[198] evaluated coordination patterns of kicking a soccer ball over a barrier in players of different skill levels. Those who were more skilled demonstrated less joint involvement at the proximal joints and greater involvement at distal joints, as if to chip a soccer ball. The ability to stabilize the proxmal hip joint and accelerate the shank was perceived as the ability to satisfy the task constraints of height clearance and target accuracy.

Novices produced larger ranges of motion throughout the entire kicking leg, in a manner similar to drive a soccer ball.[198] The individual, task and environment all effect the system and how it self-organizes. Movement patterns tend to stay in a stable, attractor state. When constraints change, the stability of this state may change until movement patterns reorganize and form a new, more stable pattern. Control parameters, such as direction, force and speed, are variables that may move a system into a new attractor state. Variability in movement patterns, exemplified by fluctuations in stability, permits flexible and adaptive motor system behavior, and the paradox between stability and variability explains how skilled athletes can produce a subtle blend of the persistent and adaptive.[199,200]

2.6.2 Variability of coordination

Variability is inherent within all biological systems, it reflects variation in both space and time.[201] One essential feature of coordinative structures is that if one segment is altered, another segment automatically varies their pattern to minimize effects of the initial movement.[163] Traditional movement science tended to associate variability with noise and performance decrements and pathology.[200] It is now recognized that coordination involving multiple degrees of freedom, a similar task outcome can be obtained in a variety of different configurations of these elements.[87] Change in the perspective regarding the role of variability can be seen in Figure 3.[200]

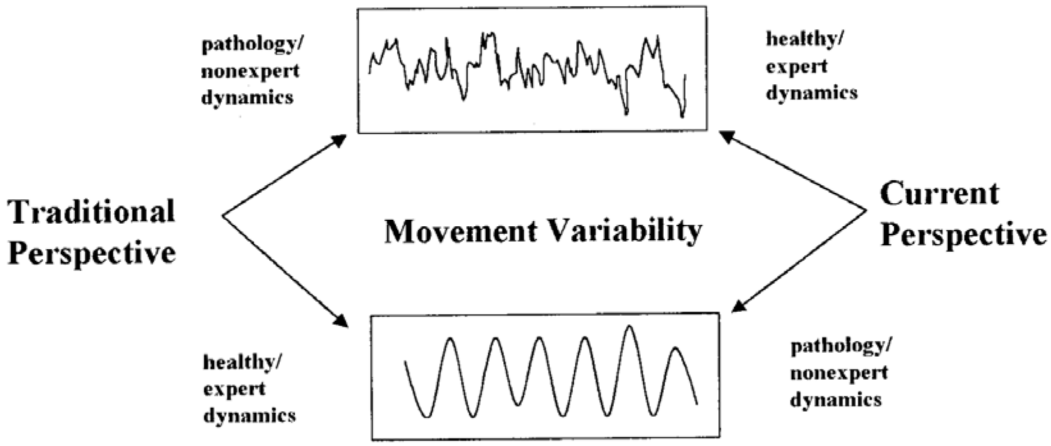


Figure 3. Changing perspectives on the role of variability in the control and coordination of movement (van Emmerik 2002)

Traditionally, variability has been thought of as noise, which interferes in the ability to achieve a desired outcome.[89] End-point variability, variability in the product of a movement or a task outcome, is based on this traditional view, which would state that variability of the product of a movement should be less in a healthy individual and greater in a less healthy individual.[202] For example, there is a rhythmicity to pitch cycle durations that should show little variability over consecutive pitches. However, stability in goal-directed performance is only achievable only through variability at the level of coordinative relations underlying that performance.[79,203] Variability has often been believed to equate with system stability or the ability of the system to offset an applied perturbation. A softball pitcher who demonstrates variability in whole body coordination, but maintains a consistent ball velocity and accuracy, would be better able to adapt to her environment of constraints. Variability allows the softball pitcher to better adapt to changes, making the system more flexible and ultimately more stable.[204] In relation to Bernstein’s DOF, variability can be seen in highly skilled athletes who can utilize the large number of degrees of freedom; whereas less skilled athletes stick to a rigidly fixed DOF.[188] There is a spectrum between too much variability and complete repeatability.[201]

Variability may also be a part of the natural learning process of movement.[205] Motor skill is representative of the ability to execute a predetermined outcome, such as a successful windmill pitch, with a high degree of certainty and maximum proficiency.[206] Skilled coordination include the anticipation of the consequences of actions at the level of the task and the anticipation of the reactive forces (interaction and gravitational torques) that are produced with these actions; these forces must be anticipated to ensure successful functional action. In order to successfully anticipate the dynamics for successful action, an individual must experience the variability of their actions and the failure of certain types and forms of their actions to achieve their end goals.[207] Within Bernstein's three stage model of motor learning, high movement and outcome variability is seen in the first stage as a learner is trying to establish coordination patterns. Less skilled athletes stay within a specific DOF and may show variability in movement patterns due to their lack of adaptations to task constraints. As an athlete acquires a new skill, gains control of coordinative structures and 'unfreezes' DOF, variability represents searching for more successful coordination patterns. Changes may be seen in the ability to control and integrate posture, motion and muscle activity to allow a variety of motor behaviors specific to a sport.[90] Newell called the last stage of motor learning 'skill', which corresponds to an optimization of the coordination pattern; referring to the efficiency in being able to exploit body segments to perform an economical and fluid movement.[208] Skilled athletes are able to freeze or unfreeze the DOF in a chain of movement to achieve the desired outcome regardless of constraints.[188] High (functional) movement variability is seen due to flexibility in exploiting information from the environment.[209] Fleisig et al.[210] found changes in variability of pitching biomechanics at different levels of development by comparing standard deviations of several kinematic parameters. Individual standard deviations were greatest in youth pitchers and decreased for those in higher levels of competition. This may show that initial variability is necessary to explore the many possibilities of movement for a selected task.

Everyone's solution to a task problem will be unique to their own organismic constraints. Thus, teaching techniques designed to promote ideal optimal movement solutions might be redundant.[194] In Bernstein's perspective of mastering redundant DOF, practice was characterized as the search for the optimal motor solutions to the problem at hand; it was seen as repeating the solving of the motor problem rather than repeating one particular solution.[85] Constraints acting on performance are more often temporary than permanent, and can be influenced by learning, age or development.[211] Through manipulation of task constraints, one can mimic constraints of specific performance, creating a learning environment in which one can seek to adapt to these changes. For example, a soccer coach may shrink the playing field to promote better ball control of the learner.

A dynamical system only offers temporary stability, or attractor, which allows an individual to develop new motor patterns.[83] At any point a system may be settled into an attractor or moving toward another attractor. Changes in control parameters cause coordination patterns to become unstable, switching to a new, more stable movement pattern. The function of control parameters is to move the system through its many different states. There comes a point (a bifurcation point) when a small change in the control parameter will specify a dramatic shift in the order parameter, with significant consequences for the system state.[83] Greater variability indicates that a system is closer to transitioning into a new movement pattern, while less variability is indicative of a more stable system.[212] Following periods of instability, quick changes between coordination patterns, called phase transitions, occur.[95, 213] Phase transitions occur as one attractor becomes unstable and the system bifurcates to a new attractor state. Distinguishing traits of a phase transition include: 1) a qualitative change in the order parameter, reflecting a reorganization of the system; 2) a sudden jump in the order parameter with a continuous change in the control parameter, without occupying intermediate states; 3) hysteresis, the tendency to remain as the control parameter is increased (or decreased) through the transition region; 4) critical fluctuations near the transition, indicated by an increase in the variability of the order parameter, that reflect the loss of stability that occurs when the basin broadens in the transition region; and 5) critical slowing down near the transition, an increase in the time required to recover from perturbation.[213] Increases in relative phase can be seen in locomotion before the transition from walking to running, where continuous variation in a control parameter, stride frequency and length, can induce bifurcations in the order parameter (relative phase).[213] Increased intersegmental variability (critical fluctuations) is a key characteristic of this phase transition.[214] In walk-to-run and run-to-walk transitions, an increase in variance of the phase coupling between modes is seen before a switch in relative phase between components, followed by a drop in variance to near zero after the transition.[215] Changes between attractor states allows an individual adapt to its environment of constraints and may also decrease risk of overuse injury.

Even in the most repetitive movements, there is some variability within body segments that is considered purposeful and healthy. For example, gait is a continuous, cyclic task, in which steps are not random but are not completely repeatable. Decrease or loss in optimal amount of variability will make the biological system more rigid. Increase beyond optimal variability will make the system more noisy and unstable. Both render the system less adaptable to perturbations and can be associated with lack of skill or health. Thus, stable yet adaptable systems maintain a rich repertoire of movement strategies containing optimal variability.[201]

A lack of variability keeps a behavior in a specific state (or attractor). In repeated motions, such as softball pitching, overuse injuries may occur by too low variability which causes repetitive local tissue stress.[163] Instead of using multiple pathways for similar movement, decreased variability stays within one pattern, potentially overstressing anatomical structures. Optimal coordinative variability distributes forces over a larger area, decreasing the risk of overuse injury.[94] Hamill et al.[95] examined the differences in continuous relative phase (CRP) variability of subjects with and without patellofemoral pain. CRP analysis takes into account both (angular) position and velocity in quantifying coordination and therefore captures the underlying spatiotemporal dynamics of intersegmental coordination.[216] They found that greater coordinative variability was present in healthy subjects, while those who experienced knee pain demonstrated lower variability. Seay et al.[217] found similar results when comparing pelvis-trunk variability in runners who have never had low back pain, those who had previous pain and those with current pain. Transverse plane coordinative variability was greatest in runners with no history of low back pain and smallest in those with current pain. Both studies may indicate healthy individuals utilize a greater number of coordination patterns for the same end task. A threshold of coordinative variability may exist, where below that level an individual may be at greater risk for overuse injury.[218] A reduced number of possible movement patterns can result in excess repetitive force on a small area. Rigid movement patterns may also create injury if individuals cannot respond appropriately to outside perturbations.[219]

In support of Bernstein's early observation, most research agrees that highly skilled athletes may increase their movement variability through release of degrees of freedom.[211,220-222]

However, there is little research on whether this holds true under specific task constraints. It has been observed that coordination of a task with extremely high accuracy demands show a constrained and pre-determined pattern, rather than a flexible one.[223] Most athletic tasks involve accuracy as part of the end goal. Arutyunyan and colleagues first looked at the functional variability of skilled and unskilled marksmen. Higher levels of variability were seen in the shoulder and elbow of highly skilled shooters in order to maintain a stable wrist position.[224] This was not found in less skilled shooters, therefore they had greater variability in the wrist, allowing for an unstable pistol while shooting. Broderick and Newell examined coordination patterns of various subjects while bouncing a ball. They found movement patterns of those who were less skilled exhibited greater variability. They concluded this may be due to the external constraints of having to match their movement pattern with the ball's bouncing.[225] Segmental coordination will provide insight into the essential timing and sequencing over biomechanical degrees of freedom and its variability will reflect the adaptability of such control.

2.6.3 Measurements of coordination

Examination of individual joint kinematics and kinetics may not be sufficient to reveal how the neuromuscular system is organized to coordinate movement.[226] Evaluating movement in terms of coordination defines the context in which they are naturally realized. The temporal patterning of muscle activities may be fixed independent of changes in the absolute magnitude of activity in each muscle. Similarly, the temporal patterning of kinematic events may be fixed independent of changes in the absolute magnitude or velocity of individual movements.[227] Movement is difficult to break into parts and analyze because the different components are interdependent. Measuring each part of movement separately does not produce an overall measure of the complexity required for success in performance. Complexity is seen within the time series of a movement sequence or strategy as it emerges over time.[163] Linear tools, such as standar deviation and coefficient of variation, to measure variability offer information about the quantity of a signal, but does not express the time dependent nature of that signal. Typically, trials of an individual's movement are averaged together. This averaged value removes the temporal variations of movement, masking the true svariability in an individual's movement pattern.[163] Linear tools also assume that this variability is random and independent of future movements. Nonlinear tools describe a time series, or a series of measurements taken at specific intervals over an uninterrupted time. Evaluating a movement in the context of time allows us to understand the ability of systems to adapts to changing conditions/constraints.[163]

Motor patterns are defined by coordination or coupling relationships between limbs (interlimb) or between segments within a limb (intra-limb intersegmental). Coupling shows the interaction between segments (or joints), indicating that motion of one can influences the other.[94] During the performance of a multicyclic behavior, the cycle-to-cycle consistency of this intralimb relationship furnishes a gauge of the ability to consistently reproduce the behavior and, therefore, can be considered a measure of the degree of coordination. One key feature of coordinative structures is that an inefficiency of one component automatically causes the other component to compensate if performance is to be maintained.[87] Vector coding is a method to assess coordination by the quantification of segmental angle trajectories, giving both spatial and temporal information.[228] Spatial information is associated with the pattern selection or relative position between segments and temportal information is the latency or relative timing between segment positions.[229]

Vector Coding utilizes segmental angle-angle plots to measure coordination and coordination variability. These plots graph two segment motions as a two-axes graph, with the position of one segment angle plotted on one axis and the second segment angle plotted on the other axis.[230] This allows for the presentation of the motion of one joint relative to another, eliminating the effects of time.[231] One advantage to vector coding is that there is no requirement for normalization, which maintains the true spatial information in the data.[232] It has also been proposed that vector coding is more suitable for clinicans who 'are more likely to think of movement in terms of joint or segment angles as opposed to phase values'.[233]

Modified vector coding has been used to analyze coordination patterns during gait and athletic tasks. Needham et al.[234] provided pelvis-lumber coordination and variability of healthy participants while walking. Pelvis and lumbar segment coordination patterns were presented throughout the gait cycle for the transverse, frontal and sagittal planes. High coordination angle variability was seen between individuals, emphasizing the need for single subject analysis.[234] Coordination patterns are different among individuals due to each person's response to imposed constraints making it important to analyze a softball pitcher individually based on her adaptations. Comparison of coordination patterns between softball pitchers may help determine optimal movement for best performance. Lower extremity intra-limb coordination variability during the triple jump has also been examined with the modified vector coding technique. The hop-step transition of the triple jump showed greater variability in less skilled jumpers compared to expert jumpers, likely due to less skilled jumpers continually refinining their technique.[235] Continuous evaluation of coupling patterns within an individual over time allows assessment of coordination strategies and their variability or stability .

2.7 METHODOLOGICAL CONSIDERATIONS

2.7.1 Isokinetic strength

Concentric, isokinetic strength of the knee, hip, trunk and elbow flexors and extensors and trunk rotators were evaluated before and after the pitch series. The softball windmill pitch movement is initiated by forward translation of the trunk propelled by the drive leg. Each segment linked in this proximal to distal pattern of activation can influence motion of its adjacent segments. Variations in motor control and physical fitness components, such as strength, can affect the efficient and effectiveness of this linked system.[88,236] Potential changes in isokinetic strength values before and after pitching series may be indicators of muscular fatigue.

2.7.2 Coordination patterns

Coordination and its variability were evaluated through a simulated softball game. Fastball pitches were used for 105 consecutive windmill pitches. Previous research has shown that softball pitchers will throw an average of 99 ± 21 pitches per game[97] and on average 15 ± 6 pitches per inning.[237] In a study of collegiate softball pitchers, the fastball was related to the greatest percentage of injury with 37% of all pitchers throwing the fastball as their pitch of choice.[2] Fatigue in collegiate baseball pitchers has been shown to occur after 62 ± 28 pitches, as assessed by 3-dimensional variable error of each upper extremity joint.[139]

Typically, development of risk assessment and screening has focused on joint range of motion, muscle strength and extensibility. However, these parameters isolate a specific joint of muscle in a non-functional way. Traditional kinematic and kinetic analyses have been used to assess specific motions and time points during athletic movement. These measurements are typically highly specific to one task or sport specific skill. Very few of these assessments have been successful in predicting injury.[110,238] None of these methods allow researchers to understand the interactions of individual motions to produce one continuous movement. Coordination measurements of the upper and lower extremities were assessed as angular motions in the sagittal plane. Coordination of rotational components of the trunk were also be measured due to their large contribution of upper extremity velocity. Additionally, few studies have addressed the possibility that the system may adapt to fatigue either increasing or decreasing coordination variability to maintain performance outcomes.

3.0 METHODOLOGY

3.1 EXPERIMENTAL DESIGN

This study utilized a cross-sectional design to evaluate coordination patterns of windmill style softball pitchers. Additionally, this study assessed variability in coordination patterns throughout a series of consecutive pitches.

3.2 PARTICIPANT RECRUITMENT

The study was approved by the Institutional Review Board at the University of Pittsburgh prior to the implementation of all research procedures. Potential participants were recruited from local university and high school softball teams. Those who were interested in participating in the study contacted the Neuromuscular Research Laboratory for more information. To ensure homogeneity of participants all potential participants were screened over the phone for inclusion and exclusion criteria as listed in the next section.

3.3 PARTICIPANT CHARACTERISTICS

3.3.1 Inclusion criteria

Individuals were eligible if they were females between 16 – 23 years of age. They must have been physically active, as operationally defined by participating in softball related activity at a minimum of 3 times per week for at least 30 minutes per session. Participants had to currently have pitched on a fast pitch softball team and have at least one-year experience pitching with a windmill style softball pitch.

3.3.2 Exclusion criteria

Individuals were deemed ineligible if they reported having previous surgery in past 12 months or current injury that interferes with ability to pitch. They were ineligible if they were knowingly pregnant.

3.4 SAMPLE SIZE

An *a priori* power analysis was conducted with G*Power 3 (Franz Faul, Universitat Kiel, Germany) based on pre- and post-pitching muscular strength values. The power analyses was completed using a t-test for difference between two dependent means, assuming an alpha of 0.05, power of at least 80%, moderate correlation between repeated measures, and a moderate effect size (d = 0.71).[239] To the author's knowledge, other studies have not provided sufficient information (means and standard deviations, along with correlation between repeated measures), to calculate effect sizes for a paired t-test under similar experimental conditions. A total of 14 subjects were needed, therefore 18 subjects were screened and recruited to account for approximately 30% subject attrition and/or data loss.

3.5 INSTRUMENTATION

3.5.1 Tanner Stage

The Tanner Stages was used to determine participant's maturation status. The Tanner Stages divides puberty into five Sexual Maturity Rating (SMR) stages by development of secondary sex characters.[240]

3.5.2 Anthropometrics

A wall stadiometer (Seca, Hanover, MD) and electronic scale (Life Measurement Instruments, Concord, CA) were used to collect participant's height and weight respectively. Leg length was measured with a cloth tape. Elbow, wrist, knee and ankle widths were measured using an anthropomometer. Upper and lower extremity anthropometric measurements were recorded in centimeters and used for the motion analysis software to build a 3-D model of the participants to calculate joint angles and segment movements.

3.5.3 Isokinetic dynamometer

A Biodex System III Isokinetic Dynamometer (Biodex Medical Systems, Shirley, NY) was used to measure peak torque and time to peak torque (milliseconds, ms) for knee, hip, trunk and elbow flexion and extension and torso rotation strength. This isokinetic dynamometer is a popular tool for the measurement of peak torque and time to peak torque.[241] The Biodex has been shown to be a reliable measure of isokinetic strength.[242] Calibration of the Biodex System III dynamometer was performed as outlined in the manufacturer's service manual.

3.5.4 Softballs

Each pitcher used a new Jugs 12" Softie Yellow Softball (JUGS Sports, Tualatin, OR). These training softballs are the same size (30.5 cm) and weight (0.2 kg) as regulation leather balls. Softballs were marked with retro-reflective tape to be tracked with the motion analysis cameras and software (Figure 4).

Figure 4. Softballs used during motion analysis

3.5.5 Radar gun

A Stalker Solo 2 sports radar gun (Applied Concepts, Inc., Plano, TX) was used to measure peak ball velocity. The radar gun was set at level 3 range, for maximum sensitivity, as recommended by the manufacturer. The Stalker Solo 2 can capture speeds up to 965.6 kilometers per hour (600 mph) at 91.4 meters (300 feet), with an accuracy of ±0.16 km/h (±0.1 mph). The radar gun has been calibrated by the manufacturer.

3.5.6 Heart rate

Heart rate (beats per minute) data was collected using a Polar heart rate monitor strap and training computer (Polar USA, Lake Success, NY). Heart rate was monitored continuously throughout the entire pitching protocol. Heart rate data was collected to ensure subjects were pitching at maximal intensity.

3.5.7 Rating of perceived exertion (RPE)

The OMNI scale for RPE was used to measure participant's perceived effort at the end of each inning pitched (Appendix A). The OMNI scale quantifies perceived effort on 0-10 scale using a picture chart with 0 corresponding to "extremely easy" and 10 meaning "extremely hard." The OMNI scale has been demonstrated to be a valid and reliable measure of effort in exercising adults.[243,244] The OMNI RPE scale was collected to monitor the subject's perceived effort throughout consecutive pitches.

3.5.8 Three-dimensional motion analysis

Upper and lower extremity kinematics were collected using the Vicon Three-Dimensional (3D) Infrared Optical Capture System (Vicon, Centennial, CO). This system used 15 wall mounted and 3 tripod mounted high-speed infrared cameras. To track movement, infrared light was reflected off 14mm retro-reflective markers placed on the participant's body following a full body custom marker set. Marker trajectory data was collected and transferred to Vicon Nexus Software (Vicon Motion Systems Inc, Centennial, CO) at a sampling frequency of 300 Hz. A five-marker wand technique, as recommended by the manufacturer's guidelines, was used for system calibration. The Vicon motion analysis system has a reported accuracy of 117μm.[245] Global coordinate system was oriented by the five-marker wand; its origin will be on the corner of the force place, positive x is toward the left side of the participant, positive y is toward the posterior direction of the participant, and positive z is directed upward, forming a right-handed Cartesian coordinate system (Figure 5). Determination of position and angular data accuracy performed in the Neuromuscular Research Laboratory has yielded a room mean square error of 0.002m and 0.254° respectively.

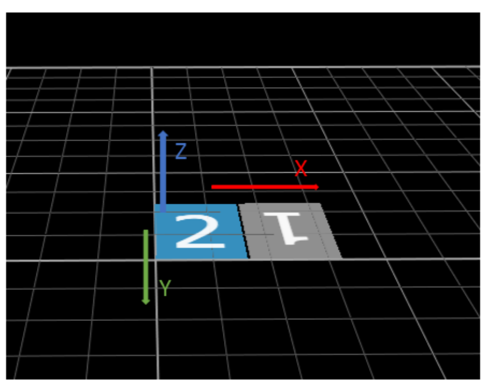


Figure 5. Global Coordinate System and force plate orientation

3.6 TESTING PROCEDURES

All testing took place at the University of Pittsburgh's Neuromuscular Research Laboratory. Each participant reported to the laboratory for one testing session lasting approximately one hour and one testing session lasting approximately two hours. Participants were asked to refrain from engaging in exercise or additional physical activity other than their daily living activities for the twenty-four hours prior to either testing session. For subjects under the age of 18, parental consent was obtained prior to subject reporting to the laboratory for assent and testing. Upon arrival to the laboratory for Day 1 of testing, inclusion and exclusion criteria were again confirmed by reviewing the participant-specific phone screen. Once inclusion and exclusion criteria were confirmed, the investigator discussed the study's aims and procedures and each participant was given the opportunity to ask questions or voice any concerns that they may have. After all questions were answered the participant signed an informed assent/consent document as required by the IRB.

Before the beginning Day 1 of laboratory testing each participant was given a five-minute general warm up, followed by baseline isokinetic strength testing. Day 2 of testing began with the subject's individual softball specific warm up to feel comfortable pitching in the lab environment and move into her full motion. A simulated game was followed by the same isokinetic strength testing protocol from Day 1. Specific testing order, shown in Figure 6, was followed for each subject.

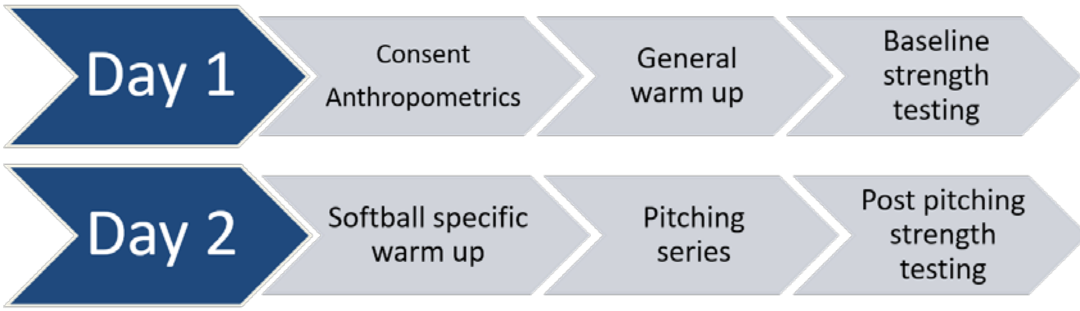


Figure 6. Testing sequence

3.6.1 Anthropometrics

Height was taken and recorded in centimeters. Body weight was taken with the participant wearing minimum clothing (shorts + sports bra) and recorded in kilograms. Bilateral leg length was measured as the standing distance from anterior superior iliac spine to ipsilateral medial malleolus. Shoulder offset was measured with an anthropometer as the vertical distance from the center of the glenohumeral joint to the marker placement on the acromion clavicular joint. Joint widths were measured with an anthropometer as the mediolateral distance across the: knee flexion axis, ankle width between lateral and medial malleoli, elbow width between medial and lateral epicondyle of the humerus, wrist width between the anterior and posterior side of the wrist in the anatomical position. Leg length and joint widths were measured and recorded in centimeters.

3.6.2 Isokinetic strength assessment

Concentric, isokinetic flexion and extension strength of the knee, hip, trunk and elbow and torso rotation strength were measured simultaneously on the Biodex System III isokinetic dynamometer. The isokinetic strength measurements have been shown to be reliable in both day-to-day testing and trial-to-trial testing for knee (ICC = 0.98)[246], hip (ICC = 0.76)[247], trunk (ICC = 0.98)[248] and elbow (ICC = 0.82)[249] strength. Isokinetic strength testing occurred at baseline (Day 1) and after each subject throws their pitch series (Figure 6). Prior to testing the Biodex System III was calibrated as specified by manufacturer's guidelines. Specific participant positioning was used to minimize variability between participants.

Isokinetic strength testing was completed at 300°/ second for concentric knee flexion and extension to replicate speed during the windmill pitch.[50,250] The participant was seated upright in the Biodex chair and mechanical adjustments to the chair will be made to standardize participant positioning. The seat back was adjusted so that the popliteal fossa of the test limb is approximately four centimeters from the edge of the chair. The chair and dynamometer position were adjusted to align the femoral condyle with the axis of rotation of the dynamometer to ensure consistent joint rotation of the knee. Two shoulder straps, a waist belt and a thigh strap were tightened to keep the participant in the same position throughout testing (Figure 7). The range of motion limits on the Biodex dynamometer were then set to each participant. The tester visually set the participant's knee in zero degrees of flexion for the "away" limit and full range of knee flexion to set the "towards" limit. The tester then placed the participant's knee at forty-five degrees of knee flexion and paused the dynamometer to record the limb weight. Start position of all practice and recorded tests began in full knee flexion.

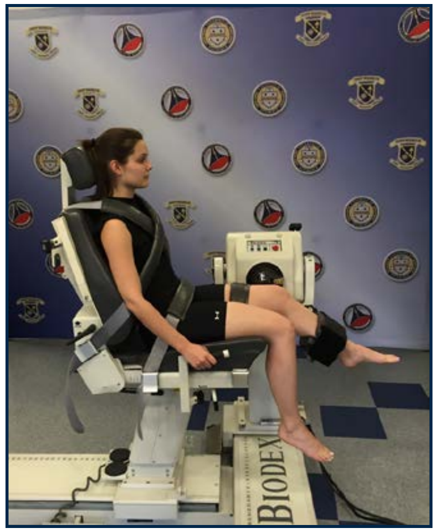


Figure 7. Isokinetic strength assessment of the knee flexors and extensors

Isokinetic strength testing was completed at 150°/ second for concentric hip flexion and extension to replicate speed during the windmill pitch.[247] The participant was supine on a fully reclined Biodex chair. The chair and dynamometer position were adjusted to align just superior and anterior to the greater trochanter with the axis of rotation of the dynamometer to ensure consistent joint rotation of the hip. The hip attachment length was adjusted so the thigh support is just superior to the popliteal fossa and secured around the thigh (Figure 8). The range of motion limits on the Biodex dynamometer were then set to each participant. The tester visually set the participant's hip in zero degrees of flexion for the "toward" limit and full range of hip flexion to set the "away" limit. Start position of all practice and recorded tests were in neutral extension.

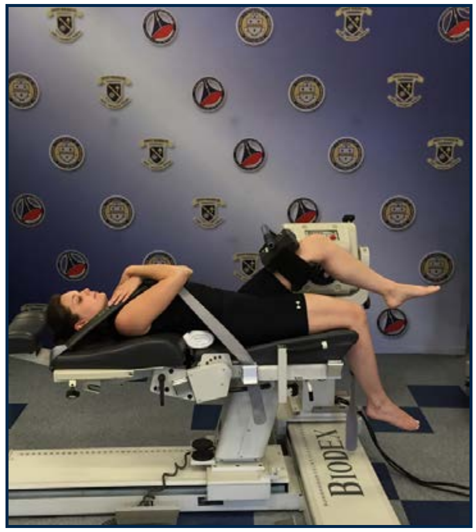


Figure 8. Isokinetic strength assessment of the hip flexors and extensors

Isokinetic strength testing was completed at 180°/ second for concentric trunk flexion and extension to replicate speed during the windmill pitch.[251,252] The participant was seated in the Dual Position Back Ex/Flex Attachment. The footrest was positioned so the femur was parallel to the seat and knees were flexed to approximately fifteen degrees. Seat Height Foot Pedal was used to adjust the participant to align the anterior superior iliac spine (ASIS) with the axis of rotation of the dynamometer to ensure consistent movement of the trunk. Lumbar pad, scapula roll and headrest were adjusted for each participant’s comfort. Pelvic and femur straps were secured to maintain stability of the lower extremity. Torso straps were crisscrossed over the chest of the participant and secured on the cervical pad for maximum restraint and comfort (Figure 9). The tester visually set the participant’s trunk in full flexion for “toward” limit and trunk extension to set the “away” limit. Start position of all practice and recorded tests was in full trunk flexion.

Figure 9. Isokinetic strength assessment of the trunk flexors and extensors

Isokinetic strength testing was completed at 180°/ second for concentric trunk right and left rotation to replicate speed during the windmill pitch.[253] The participant was seated upright in the Biodex chair so that the axis of rotation of the Torso Rotation Attachment was aligned with the long axis of the participant's spine. Hip pads were tightened against the posterior pelvis to restrict lower body movement and a Velcro strap was tightened around the back so the upper body was as tight as possible against the chest pad without causing discomfort. Leg pads were secured mid-femur with Velcro straps to stabilize the legs (Figure 10). The tester set the participant's range of motion limits as full right rotation for "away" limit and full left rotation for "toward" limit. Participants were instructed to concentrate on using the trunk muscles rather than the arms or shoulders to perform the axial rotation movements. Start position of all practice and recorded tests was with the participant fully rotated toward the left.

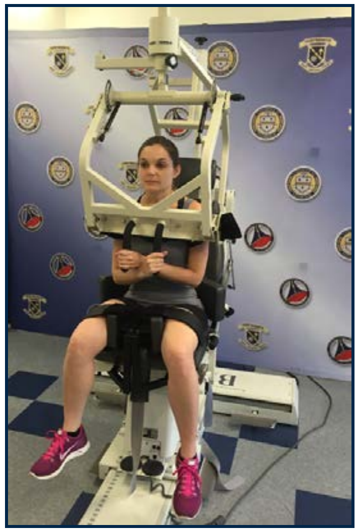


Figure 10. Isokinetic strength assessment of the trunk rotators

Isokinetic strength testing was completed at 180°/ second for concentric elbow flexion and extension to replicate speed during the windmill pitch.[254,255] The participant was seated upright in the Biodex chair and mechanical adjustments to the chair were made to standardize participant positioning. The Biodex shoulder attachment, with cuff removed, was attached to the dynamometer, which was rotated to 30°. The limb support was attached to the same side of the chair as the testing arm and angled downward to allow full elbow extension. The elbow was rested on the limb support and the chair and dynamometer position were adjusted to align with the center of the trochlea and capitulum, bisecting the longitudinal axis of the shaft of the humerus, with the axis of rotation of the dynamometer to ensure consistent joint rotation of the elbow. Two shoulder straps and a waist belt were tightened to keep the participant in the same position throughout testing (Figure 11). The tester visually set the participant's elbow in zero degrees of flexion for the "away" limit and full range of elbow flexion to set the "toward" limit. Start position of all practice and recorded tests were in full elbow flexion.

Figure 11. Isokinetic strength assessment of the elbow flexors and extensors

After verification of the participant's body position and dynamometer settings, the participant was given one set of practice trials at 50% perceived maximal effort and a second set at 100% perceived maximal effort. Each practice trial consisted of three repetitions of flexion and extension or rotation. For practice and test trials, the tester instructed the participant to begin in the start position and begin reciprocal contractions of "pushing and pulling as hard and as fast as you can" after a countdown of "3 – 2 – 1 – GO." A one-minute resting period was given to the participant before one set of five maximal repetitions. This was used as the measured trials and the participant was instructed give 100% maximum effort and go as "as hard and as fast as you can". Testing was completed bilaterally for the knee and hip and only pitching arm elbow flexion and extension.

3.6.3 Softball set up

Biomechanical data was collected at 300Hz. All participants used their own softball glove and a 12-inch regulation size softball was provided by the investigator of this study. A 2.1m by 2.1m (7ft x 7ft) Portable Bow Net with strike zone was set up behind home plate (Figure 12). A pitching location was taped off 9.14 meters from the back end of home plate (Appendix B). This pitching location was on a level platform built around the force plates. Peak ball velocity was taken and recorded by a Stalker Solo 2 sports radar gun as kilometers per hour (kph) for a total of 40 pitches. The radar gun was positioned directly behind the center of the Portable Bow Net strike zone, 3.20 meters behind the net and 0.76 meters above the floor. The radar gun was set to face the participant at the level of ball release.

Figure 12. Alignment of force plate/pitching rubber, netting, radar gun

3.6.4 Participant preparation

On Day 2 of testing, preparation for biomechanical assessment of the softball windmill pitch began using the anthropometric measurements including weight, height, leg length (standing distance from anterior superior iliac spine to medial malleolus), elbow, wrist, knee, and ankle widths and shoulder offset. These measurements were entered in the Vicon Nexus software to create a custom model from the 3D coordinate data. Each subject was given a Polar heart rate monitor to wear during the pitch series. Heart rate was recorded at the end of each inning and the RPE scale was explained to the subject as an assessment of effort felt while pitching.

Kinematics during the softball windmill pitch were calculated based on the three-dimensional coordinate data of 31 14mm retro-reflective markers placed on the participant's torso, upper and lower extremities. The orientation and position of each rigid segment's local coordinate system was determined by reconstructed marker positions per segment. For the static capture, retro-reflective markers were placed on the spinous process of the 7th cervical vertebra (C7), sternal notch, xyphoid process, the 1st sacral vertebrae (S1), non-pitching lateral aspect of the upper arm and forearm and bilaterally on the following landmarks: acromioclavicular joint, lateral and medial humeral epicondyle, radial and ulnar styloid, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), medial and lateral femoral epicondyle, medial and lateral malleolus, lateral aspect of 1st and 5th metacarpophalangeal joint, and posterior aspect of the heel (Figure 13). Additionally, a 4 non-collinear marker cluster, using 9.5mm markers, was placed on the posterior humerus and radius of the pitching arm, bilateral posterior thigh and shank. A 3 non-collinear marker cluster was placed over the spinous process of the 3rd thoracic (T3) and 3rd lumbar vertebrae (L3) (Figure 14).

For dynamic trials, non-pitching lateral upper arm, lateral humeral epicondyle, lateral forearm and bilateral acromioclavicular joint, radial and ulnar styloid, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), lateral malleolus and posterior calcaneus markers and all 4 marker and 3 marker clusters were kept on. (Figure 15)

Prior to data collection of pitches, each participant was allowed her normal pitching warm-up routine until she verbally stated that she felt warmed up and comfortable with the testing environment.

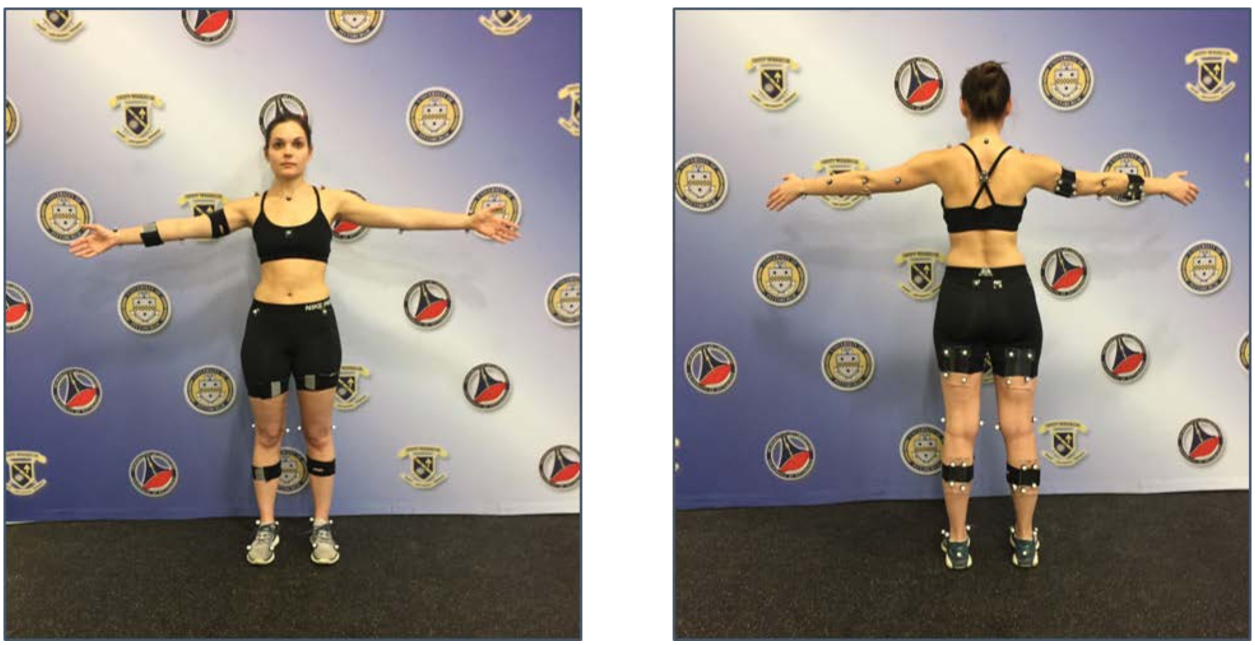


Figure 13. Marker placement for static calibration of kinematic assessment

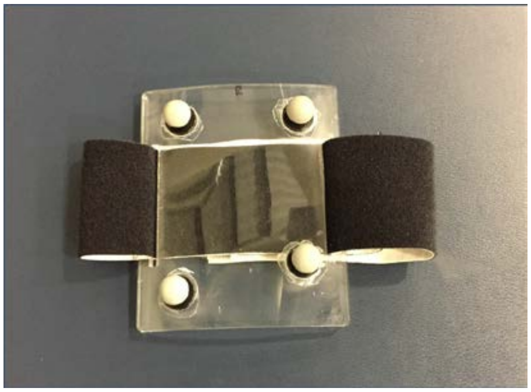


Figure 14. Non-collinear marker cluster

Figure 15. Marker placement for dynamic trials of kinematic assessment

3.6.5 Softball windmill pitch

The camera system was calibrated using the manufacturers recommended guidelines and the global coordinate system (Figure 4) was defined prior to the testing session with the subject. Once participant-preparation had concluded, a static calibration trial was collected with the participant standing upright on the force plate in the anatomic neutral position with their arms abducted to ninety degrees and palms facing forward. Verbal instruction was given to "Point your toes forward, place your feet directly under your hips, keep your knee and hips as straight as possible, and hold still." More specific segment position instructions were given if needed upon visual inspection. A three second calibration trial was collected while the participant remains still in this position. This trial was then labeled and processed in the Nexus software to establish segmental coordinate systems specific to the subject's biomechanical model.

Participants began by standing with each foot on a separate force plate facing the Portable Bow Net. A pitching rubber was taped off mid-length of the force plate (Figure 16).

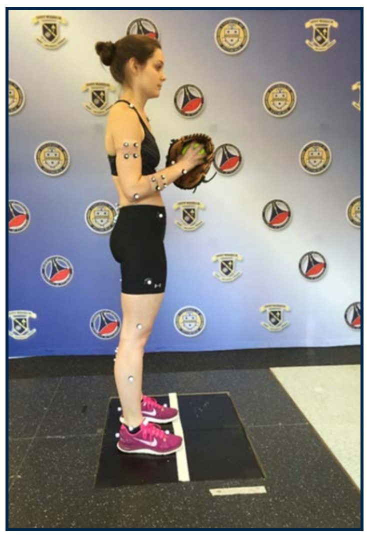


Figure 16. Starting position for softball pitchers

Participants pitched similar to a softball game, with 105 total pitches broken up between 15 pitches in 7 innings. The first 5 pitches of the first inning were collected to get a baseline measure. The last 5 pitches of all innings were captured for data analysis to determine any biomechanical changes due to pitching an entire inning (Figure 17). Heart rate was recorded and the participant was asked to rate their perceived effort on a scale of 0 – 10 at the end of each inning. A four-minute rest was given between innings.

Figure 17. Pitches collected for data analysis

Pitch velocity was recorded with a Stalker Solo 2 sports radar gun for all pitches used in analysis and recorded in kilometers per hour (kph).

3.7 DATA REDUCTION

3.7.1 Upper and lower extremity strength

Peak torque and time to peak torque for isokinetic knee, hip, trunk and elbow flexion and extension and trunk rotation strength was recorded. Peak torque was defined as the average peak torque normalized to body weight (%BW) during the five reciprocal trials. Time to peak torque was defined as the time from the initiation of motion in the respective direction to the recorded peak torque for each repetition. An average of the five reciprocal trials was recorded for time to peak torque for all strength measures.

3.7.2 Pitch Accuracy

Pitch accuracy was recorded as a dichotomous variable, either passed through the defined strike zone or did not. The number of strikes thrown per inning were summed and divided by the total number of pitches recorded (5). Pitch accuracy was then reported as a proportion of strikes thrown, as a decimal.

3.7.3 Windmill Pitch Cycle

Pitch cycle time was calculated as the time, in milliseconds, from the beginning of Phase 2 until ball release. Stride length was calculated as the maximum distance from the second toe of the drive foot to the heel of the stride foot in the forward direction, in meters.

3.7.4 Upper and lower extremity kinematics

Sets of five fastball pitches were collected and used for analysis (Figure 15). All raw marker trajectory was recorded and filtered using the Vicon Nexus software. Raw marker displacement data were examined using a Fourier analysis, which revealed an optimal cutoff frequency of 6Hz. This cutoff appeared to be free from noise and showed that the signal is minimally attenuated. Displacement data were low-pass filtered with a 6Hz fourth order Butterworth filter and Central Finite Difference method was used to derive marker velocity and acceleration. The 3D positions of the retroreflective markers were reconstructed in the global coordinate system, with the X axis pointing toward home plate, the Z axis was vertical pointing upwards, and the Y axis perpendicular to both X and Z directions. Based on the custom marker set, subject-specific models were created in Visual 3D (C-Motion, Germantown, MD). The estimation of hip, knee, and ankle joint centers and the definition of segmental coordinate systems used subject-specific anthropometric data.

In Visual 3D, trial data were cropped from one point prior to beginning analysis point, to minimize endpoint errors, until ball release and then data was normalized to 101 points. Local coordinate systems for the segments were determined from the static calibration trial. Segment angles were defined as the angle of the segment relative to the right horizontal of the laboratory coordinate system (Figure 18). Joint angles were expressed according to the International Society of Biomechanics recommendations.[256,257] Three-dimensional joint flexion/extension angle data were calculated with Euler angle rotational decomposition using the right-hand rule in a sequence of X, Y, Z; where X values denote flexion/extension, Y values abduction/adduction and Z values axial rotation [258,259] The Euler ZXY sequence was used to calculate thoracic and pelvic rotation.[260,261]

Thoracic and pelvic orientation was calculated within the global coordinate system. ISB recommendations were used to define the thoracic reference frame: spinous process of the 7th cervical vertebrae (C7) and 8th thoracic vertebrae (T8), sternal notch and xiphoid process.[257] The origin of the pelvis segment coordinate system was the mid-point between the two ASIS markers that defined the Y axis. The X axis was directed in an anterior direction perpendicular to the Y axis from the mid-point of the ASIS markers and mid-point between the PSIS markers. The Z axis was formed by the cross product of the X and Y axis.[262]

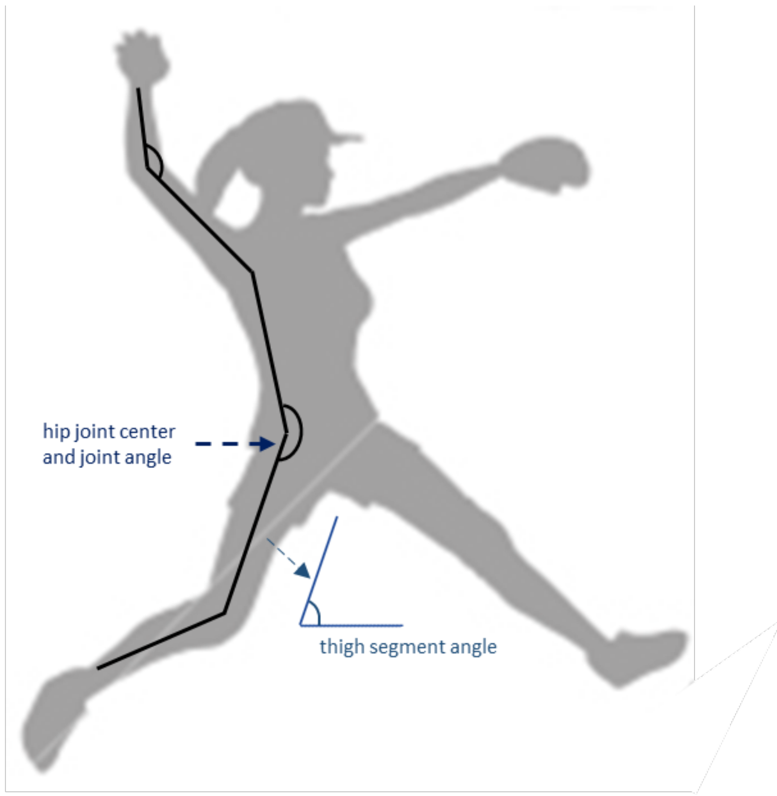


Figure 18. Subject joint center marking, joint angles and segment angles

Pitch cycle duration was calculated as time from the pitching arm humerus was in line with the trunk (Phase 2) until ball release and recorded in milliseconds. Windmill pitch stride length was calculated as the anterior-posterior distance from drive leg toe marker to stride leg heel marker and recorded in meters.

3.7.5 Measures of coordination

Four measures of inter-segmental and intra-limb coordination were calculated to provide spatial data. Modified vector coding was used to quantify the continuous dynamic interaction between segments angles of:

- Drive Leg Thigh flexion/extension v Pelvis axial rotation,
- Pelvis axial rotation v Thoracic axial rotation,
- Pelvis axial rotation v Pitching Arm Humerus flexion/extension and
- Pitching Arm Humerus flexion/extension v Forearm flexion/extension.

Modified vector coding measured the coordination between two segments or joints, as calculated by the angle of the vector between successive points on the angle-angle plot relative to the right horizontal. This measurement provided an angle, called the coupling angle (γ), between 0° and 360° for each successive interval of the time series.[234]

Segment angles were normalized and time scaled to 100% of the pitch cycle. Segment angle-angle diagrams were created with the proximal segment on the horizontal axis and the distal segment on the vertical axis (Figure 19).

For each instant (i) during the normalized pitch cycle, a coupling angle (γ_i) was calculated based on the angle from the right horizontal of a vector connecting the proximal (θ_P) segment angles and consecutive distal (θ_D) segment angles.[234]

$$y_i = \text{Atan}\left(\frac{\theta_{D(i+1)} - \theta_{D(i)}}{\theta_{P(i+1)} - \theta_{P(i)}}\right) * \frac{180}{\pi} \qquad \text{if } \theta_{P(i+1)} - \theta_{P(i)} > 0$$

$$y_i = \text{Atan}\left(\frac{\theta_{D(i+1)} - \theta_{D(i)}}{\theta_{P(i+1)} - \theta_{P(i)}}\right) * \frac{180}{\pi} + 180 \qquad \text{if } \theta_{P(i+1)} - \theta_{P(i)} < 0$$

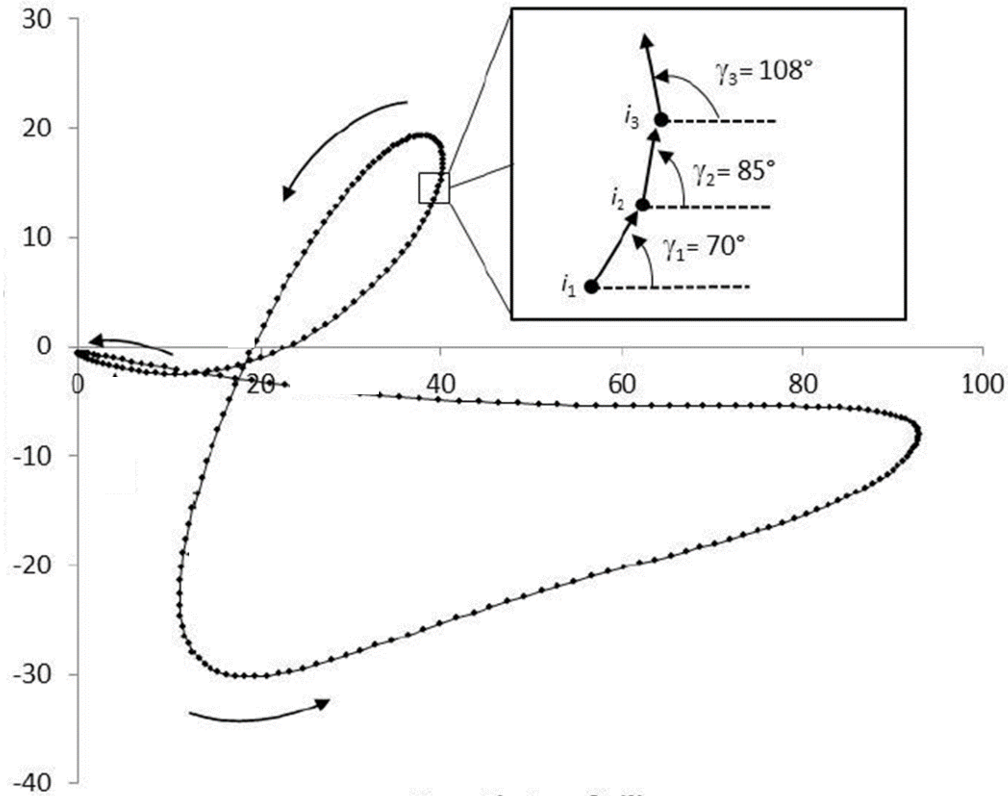


Figure 19. Angle-angle diagram with coupling angle (γ) determined by the vector orientation between three adjacent data point on time on the angle-angle diagram relative to the right horizontal (Needham 2014)

To ensure the angle produced was not affected by the zero-crossing, the following conditions were applied to identify the quadrant the angle of interest fell in:

$$
y_i = \begin{cases} y_i = 90 \text{ when } \theta_{P(i+1)} - \theta_{P(i)} = 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} > 0 \\ y_i = -90 \text{ when } \theta_{P(i+1)} - \theta_{P(i)} = 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} < 0 \\ y_i = -180 \text{ when } \theta_{P(i+1)} - \theta_{P(i)} < 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} = 0 \\ y_i = \text{undefined when } \theta_{P(i+1)} - \theta_{P(i)} = 0 \text{ and } \theta_{D(i+1)} - \theta_{D(i)} = 0 \end{cases}
$$

Where γ_i was the coupling angle and θ_i was the segment angle to the *i*th data point, D = distal segment, P = proximal segment. Coupling angle (γ_i) was corrected to present a value between 0° and 360°.[263,264]

$$\gamma_i = \begin{cases} Y_i + 360 & Y_i < 0 \\ Y_i + 360 & Y_i \geq 0 \end{cases}$$

3.8 STATISTICAL ANALYSIS

Statistical analysis was conducted using IBM SPSS Statistics 21 (IBM Corp., Armonk, NY). Descriptive statistics were calculated for all variables (means and standard deviations, medians and interquartile ranges, as appropriate). Data were tested for normality using Shapiro Wilk tests. Statistical significance was set *a priori* at alpha = 0.05, two-sided.

3.8.1 Specific aim 1 and 2

To characterize coordination patterns and evaluate variability, coupling angle at the beginning of each Phase 2 – 5 individually and average coupling angles were calculated. The disadvantage of plotting inter-segmental coordination is that it does not lend itself to quantitative analysis or allow for traditional statistical between-pattern comparisons.[205] Due to the coupling angle (γ) being directional in nature, circular statistics were applied to calculate average coupling angle ($\bar{y}$) based on the average horizontal ($\bar{x}_i$) and vertical ($\bar{y}_i$) components at each instant.[232,265]

$$\overline{x}_i = \frac{1}{n}\sum_{i=1}^{n} \cos \gamma_i$$

$$\overline{y}_i = \frac{1}{n}\sum_{i=1}^{n} \sin \gamma_i$$

The following equations were applied for the average coupling angle to present a value between 0° and 360°.

$$\overline{\gamma}_i = \begin{cases} \mathrm{Atan}\left(\frac{\overline{y}_i}{\overline{x}_i}\right)\frac{180}{\pi} & \overline{x}_i > 0,\ \overline{y}_i > 0 \\ \mathrm{Atan}\left(\frac{\overline{y}_i}{\overline{x}_i}\right)\frac{180}{\pi} + 180 & \overline{x}_i < 0 \\ \mathrm{Atan}\left(\frac{\overline{y}_i}{\overline{x}_i}\right)\frac{180}{\pi} + 360 & \overline{x}_i > 0,\ \overline{y}_i < 0 \\ 90 & \overline{x}_i = 0,\ \overline{y}_i > 0 \\ -90 & \overline{x}_i = 0,\ \overline{y}_i < 0 \\ \text{undefined} & \overline{x}_i = 0,\ \overline{y}_i = 0 \end{cases}$$

Utilizing the data normalized to one pitch cycle, length of average coupling angle ($\overline{r}_i$) of five consecutive pitches (Figure 15) was calculated per:

$$\overline{r}_i = \sqrt{\overline{x}_i^{\,2} + \overline{y}_i^{\,2}}$$

Finally, coupling angle variability (CAV_i) was calculated for each average coupling angle per:

$$CAV_i = \sqrt{2\,(1 - \bar{r}_i)} * \frac{180}{\pi}$$

Repeated measures analysis of variance (ANOVA) were used for each individual pitcher to determine if there were changes in average coupling angle and its variability throughout consecutive innings.

The pattern of coordination for each interval of the time series was then defined as in-phase (both segments/joints moving in the same direction at the same time) or anti-phase (the two segments/joints moving in the opposite direction at the same time).[75] Proximal phase is defined as a fixed distal segment with movement of the proximal segment and distal phase considered the opposite action.[94] To best quantify coordination patterns to determine change, each pitch cycle coupling angles were defined as in-phase or anti-phase using 45° bins widths (Figure 20). The frequency that each coordination mode occurred as a percentage of the total coordination was then calculated for the entire pitch cycle.

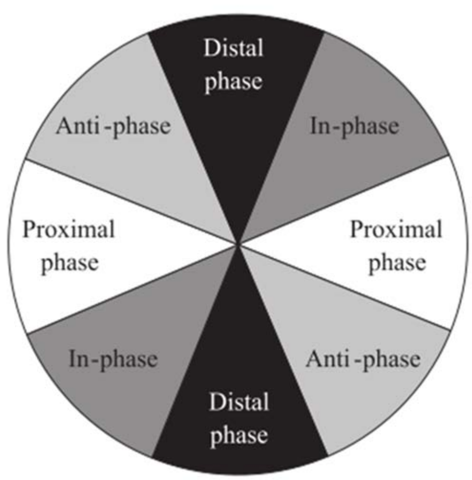


Figure 20. Polar plot showing the classification of coordination pattern from the coupling angle

3.8.2 Specific aim 3

Concentric muscular strength of the knee, hip, trunk and elbow flexors and extensors and trunk rotators were measured to determine the effects that pitching may have. Muscular fatigue was quantified as the percentage change in strength values from baseline to post-pitching session for all strength variables. The change in muscular strength pre-to post pitching of a simulated game was tested using paired samples t-tests, if data met the assumption of normality. When the assumption of normality was not met, Wilcoxon signed ranks tests were performed.

3.8.3 Specific aim 4

To assess pitching performance throughout a simulated game, ball velocity and accuracy was assessed for all fastball pitches collected (Figure 15). The first five pitches of the first inning were considered baseline data. If the assumption of normality was met, one way repeated-measured analyses of variance (ANOVA) was used to assess changes in pitching performance between innings during a simulated game. If the assumption of normality was not met, the corresponding non-parametric test (Friedman ANOVA) was used. If the omnibus test was statistically significant, post hoc pairwise comparisons were conducted using the Bonferroni correction to avoid inflation of Type I error.

4.0 RESULTS

The purpose of this study was to characterize coordination patterns and evaluate their variability. Coordination patterns were assessed as average coupling angle from the beginning of Phase 2 of the softball windmill pitch until ball release. The secondary purpose of this study was to examine muscular fatigue and pitch performance. Differences in muscular strength at baseline and after pitching were assessed using a paired t-test or Wilcoxon signed ranks tests, as appropriate. A one way repeated-measured analyses of variance (ANOVA) was used to assess changes in ball velocity and a Friedman ANOVA was used.

4.1 SUBJECTS

A total of 14 current softball pitchers volunteered for this study. Participant demographic information is displayed in Table 1. Each of the 14 volunteers successfully completed baseline and post pitching strength testing and all 105 consecutive fastball pitches.

Table 1: Subject demographic data

	Softball Pitchers (n=14)
Age (years)	17.92 ± 2.31
Height (cm)	166.42 ± 8.67
Weight (kg)	72.23 ± 12.62
Tanner Stage	5.00 ± 0.00
Number of Years Pitching (years)	8.83 ± 2.12
Number of Years pitching (% age)	48.92 ± 6.16

n = number of subjects

mean ± standard deviation

4.2 SPECIFIC AIM 1 & 2: WINDMILL PITCH COORDINATION PATTERNS

Average coupling angle of all five pitches per 100 time points and coupling angle variability (CAV) were calculated for each segment pair for baseline and all innings (Table 2).

Table 2. Average coupling angle and coupling angle variability (CAV)

			baseline	1	2	3	4	5	6	7
Drive Leg v Pelvis	average coupling angle	mean (sd)	113.20 (40.25)	113.01 (38.51)	108.42 (38.18)	111.05 (43.32)	112.60 (40.72)	110.78 (43.87)	112.65 (39.34)	111.39 (38.73)
		median	111.74	110.52	99.25	102.16	114.21	114.40	117.12	105.66
		(1Q, 3Q)	(88.19, 133.57)	(88.81, 144.20)	(89.62, 138.25)	(85.29, 141.50)	(80.89, 139.84)	(80.24, 148.24)	(84.03, 143.93)	(84.82, 147.77)
	CAV	mean (sd)	85.92 (5.57)	86.47 (6.26)	86.07 (5.65)	85.59 (5.27)	86.25 (5.60)	86.12 (6.07)	86.59 (5.80)	86.64 (5.83)
		median	86.05	86.32	85.52	85.31	85.58	85.67	87.00	86.31
		(1Q, 3Q)	(83.12, 88.40)	(82.37, 89.32)	(82.44, 89.03)	(81.77, 88.23)	(81.81, 90.33)	(82.22, 89.53)	(82.60, 91.38)	(83.00, 91.17)
Pelvis v Torso	average coupling angle	mean (sd)	101.98 (39.11)	101.98 (39.11)	99.94 (37.79)	108.64 (43.03)	100.98 (41.48)	107.13 (44.72)	102.81 (42.28)	107.76 (39.84)
		median	114.70	108.97	110.06	103.45	96.38	102.80	105.82	114.53
		(1Q, 3Q)	(69.06, 125.77)	(75.97, 140.28)	(92.42, 117.57)	(87.54, 134.67)	(82.68, 140.25)	(77.90, 147.74)	(79.05, 131.07)	(83.74, 136.88)
	CAV	mean (sd)	84.76 (5.94)	84.76 (5.94)	85.32 (5.94)	85.15 (5.66)	84.55 (6.32)	84.99 (6.06)	85.15 (6.09)	86.21 (5.94)
		median	88.33	86.44	86.68	86.42	85.32	86.65	86.01	86.27
		(1Q, 3Q)	(79.55, 88.78)	(80.65, 88.86)	(82.38, 88.17)	(82.57, 87.20)	(81.79, 88.37)	(81.24, 87.65)	(81.46, 87.90)	(82.01, 89.14)
Pelvis v Humerus	average coupling angle	mean	247.99 (53.42)	247.99 (53.42)	231.83 (63.62)	234.95 (58.09)	241.17 (54.65)	241.52 (54.80)	231.13 (70.74)	235.31 (58.21)
		median	263.90	262.28	262.54	260.00	262.30	262.33	261.75	260.71
		(1Q, 3Q)	(259.69, 266.83)	(258.62, 266.37)	(225.00, 265.86)	(226.67, 266.13)	(258.15, 265.47)	(258.75, 266.53)	(257.67, 265.27)	(232.33, 265.57)
	CAV	mean	109.86 (1.07)	109.86 (1.07)	109.59 (1.70)	109.24 (1.08)	109.36 (1.51)	109.37 (1.71)	109.00 (2.01)	109.01 (2.08)
		median	109.79	110.16	109.50	108.92	109.20	109.20	109.13	109.12
		(1Q, 3Q)	(108.83, 111.00)	(108.01, 110.78)	(108.11, 111.44)	(108.59, 110.42)	(108.20, 110.67)	(108.17, 110.79)	(107.20, 110.37)	(107.11, 110.51)
Humerus v Forearm	average coupling angle	mean	206.74 (53.87)	206.91 (53.84)	206.20 (53.74)	206.60 (53.92)	206.82(53.88)	206.53 (53.84)	207.06 (53.70)	206.51 (53.77)
		median	224.13	223.23	222.53	222.52	223.27	223.46	223.36	221.57
		(1Q, 3Q)	(221.18, 224.78)	(222.04, 224.29)	(220.77, 223.03)	(220.46, 223.59)	(220.85, 224.97)	(219.08, 224.20)	(220.78, 225.38)	(219.41, 224.91)
	CAV	mean	110.38 (13.30)	110.24 (13.45)	110.05 (13.27)	109.98 (13.35)	110.24 (13.37)	110.20 (13.34)	110.36 (13.03)	110.23 (13.30)
		median	114.14	114.34	113.89	113.62	113.91	114.12	114.11	113.91
		(1Q, 3Q)	(113.45, 114.65)	(113.13, 115.21)	(112.84, 115.00)	(112.93, 114.83)	(113.19, 114.85)	(112.75, 114.67)	(113.11, 115.00)	(113.44, 114.78)

mean (standard deviation)
median (1st quartile, 3rd quartile)

Normality testing of the change in average coupling angles and variability, using a Shapiro-Wilk test, was completed to determine appropriate testing methods. A Friedman one way repeated-measured analyses of variance (ANOVA) was used to assess changes in mean angle and variability over each inning. No statistically significant differences were seen, Table 3

Table 3. Friedman Test of average coupling angle and CAV across innings

	average coupling angle		CAV	
	chi-square	p-value	chi-square	p-value
Drive Leg v Pelvis	3.909	0.790	4.364	0.737
Pelvis v Torso	8.455	0.294	11.697	0.111
Pelvis v Humerus	7.182	0.410	13.000	0.072
Humerus v Forearm	10.788	0.148	4.242	0.751

significance at $p < 0.05$

Average coupling angles were divided into coordination patterns: in-phase (rotate in the same direction) or anti-phase (rotate in the opposite direction). When coupling angles parallel the horizontal or vertical axis, movement of one segment dominates.[263] Average coupling angles were plotted within a unit circle divided into eight 45° bins (Appendix C). Frequency distribution was calculated as the number of times the coupling angle lies within one of the eight coordination pattern bins of the windmill pitch.

Softball pitching performance was used as criteria to compare potential differences in coordination between pitchers, subjects were ranked from highest sum of all pitch velocities to the lowest as well as greatest standard deviation between all pitches to the lowest. SB04 had the lowest overall sum of pitch velocity and the second highest standard deviation while SB10 has the highest sum of pitch velocity and the second lowest standard deviation. Exemplar average coupling angles plotted within a unit circle are shown below for baseline and select innings to show the individual nature of coordination patterns (Figure 21 – Figure 35). Polar plots for baseline and all subsequent innings of SB04 and SB10 can be found in Appendix D. Additionally, frequency distribution, defined as the number of times the average coupling angle lies within one of the four coordination patterns (proximal, distal, in-phase and anti-phase) at each of 100 time points, are shown below each set of polar plots. Frequency distributions give a more traditional visualization, highlighting the individualized coordination pattern each subject utilizes to complete the same windmill pitch (Figure 22 – Figure 36).

Figure 21. Polar plot of SB04 Humerus v Forearm for baseline and inning 7

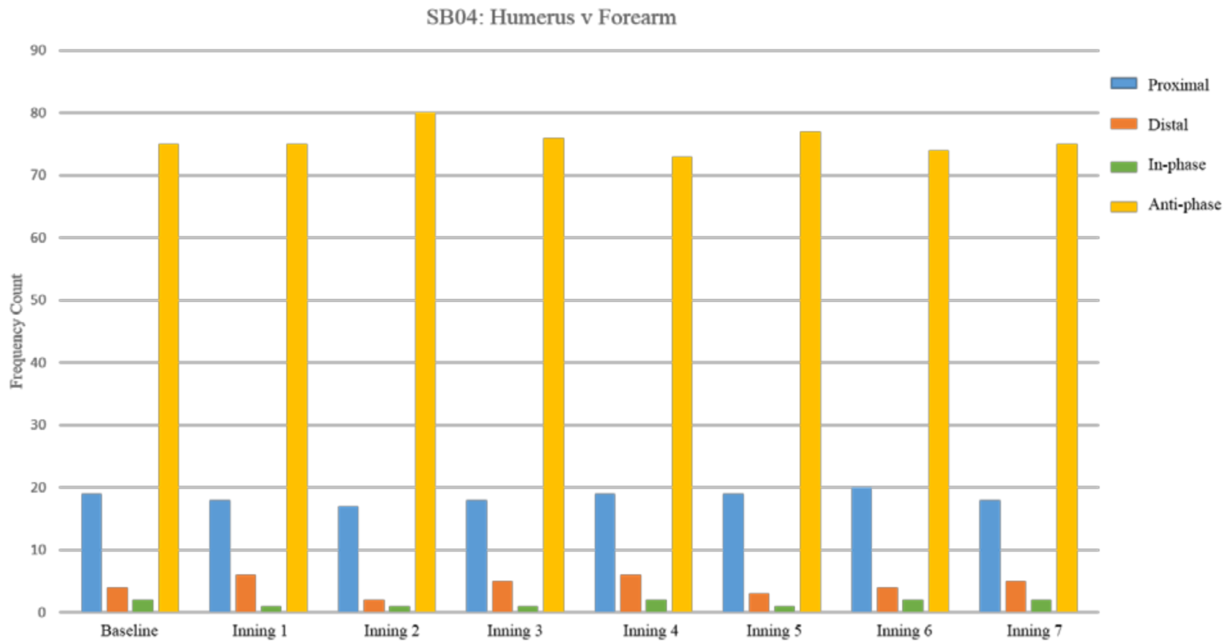


Figure 22. SB04 Humerus v Forearm coordination pattern frequency counts

For SB04 Humerus v Forearm, anti-phase dominance remains throughout all innings pitched, as observed by the large distribution between 292.5°-337.5° of the polar plot (Figure 21). This indicates the Humerus and forearm are moving in the opposite directions at the same time. Continued reliance of anti-phase coordination pattern is also seen through the frequency distribution, with highest frequency count being shown in the yellow bars.

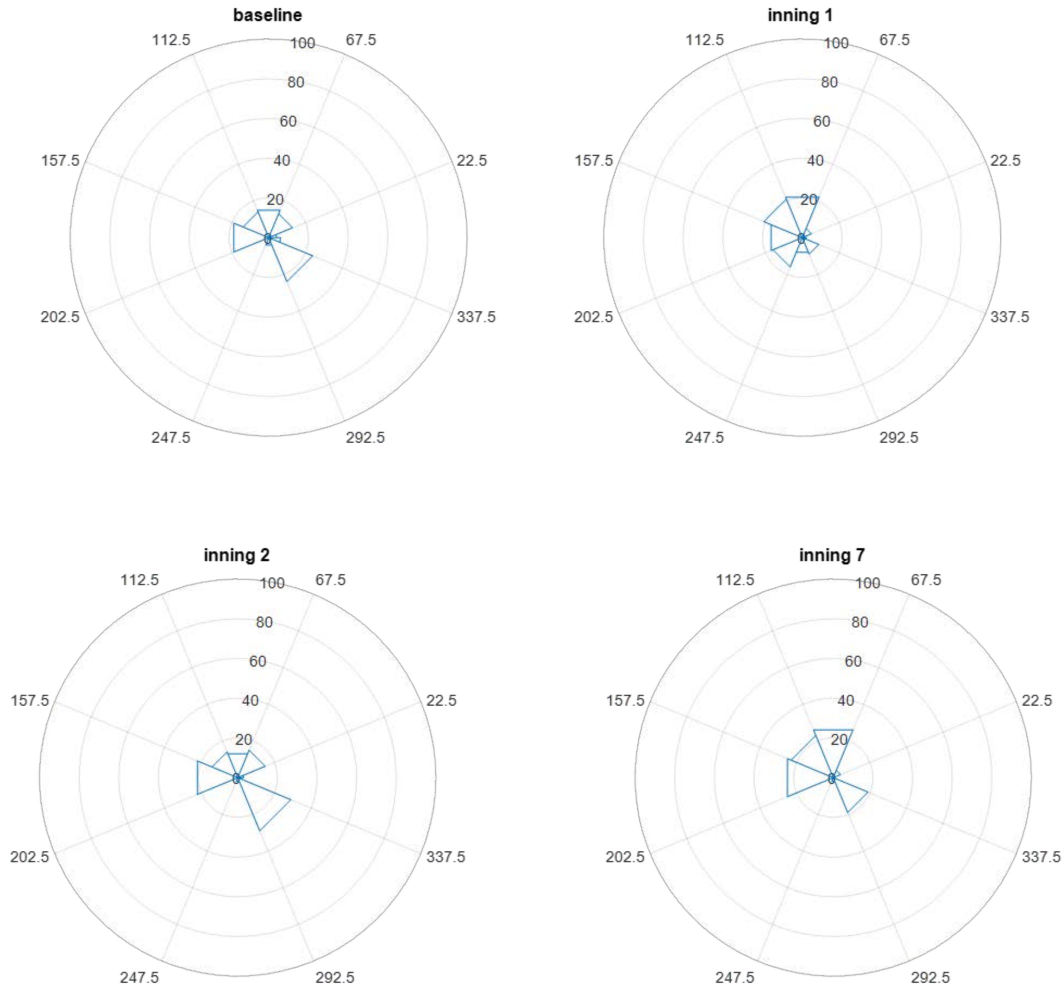


Figure 23. Polar plot of SB04 Drive Leg v Pelvis for baseline and innings 1, 2, 7

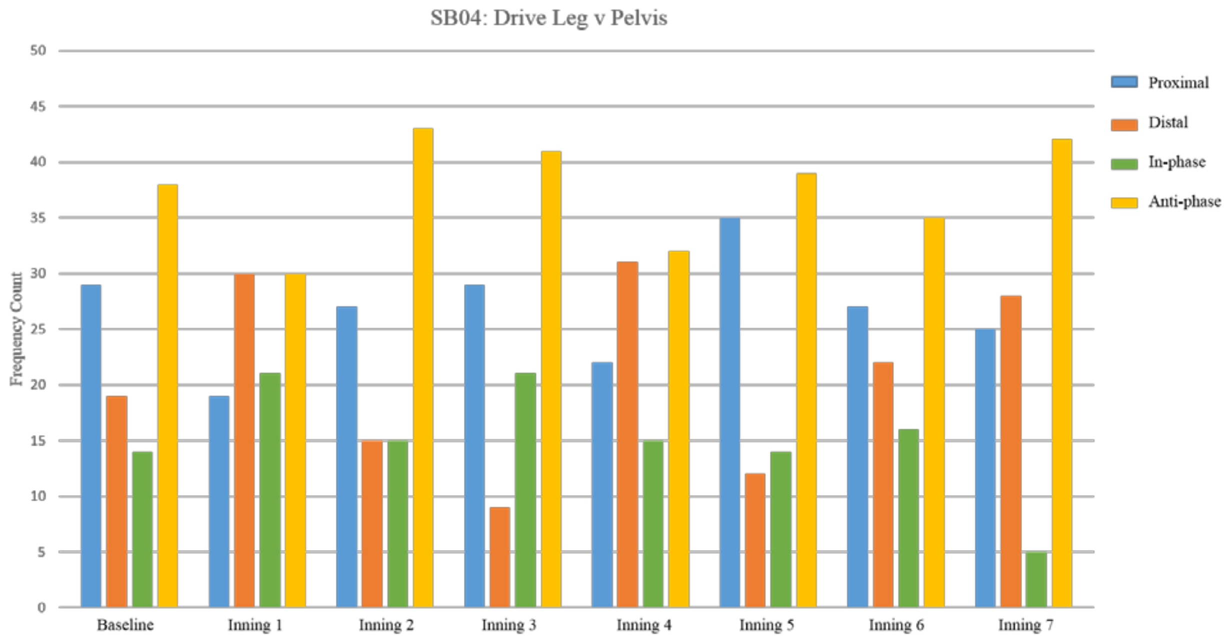


Figure 24. SB04 Drive Leg v Pelvis coordination pattern frequency counts

Drive Leg v Pelvis shows multiple changes over innings between coordination patterns, although one is never highly dominant (Figure 23). For example, baseline shows slight preference on anti-phase movement by more average coupling angles falling around between 292.5°-337.5° while Inning 1 demonstrates more of a balance between anti-phase and distal coordination patterns. Again, in the frequency distribution an increased count of anti-phase coordination is seen above all others across innings.

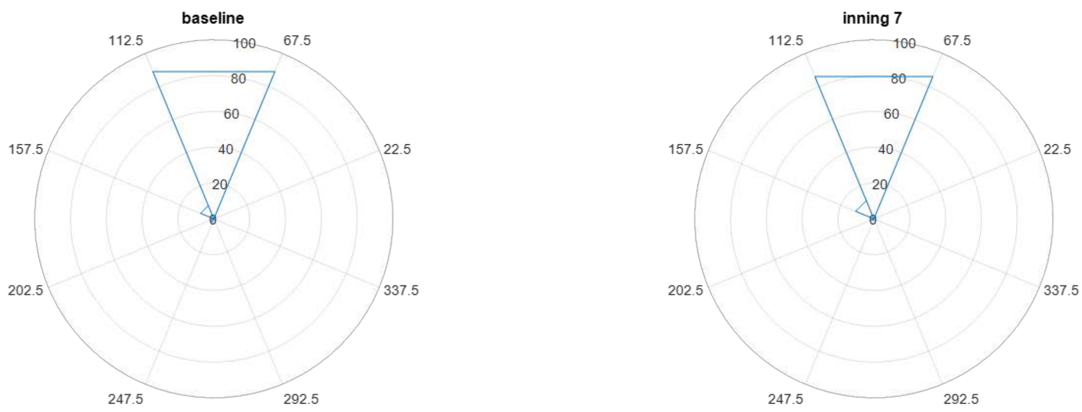


Figure 25. Polar plot of SB04 Pelvis v Humerus for baseline and inning 7

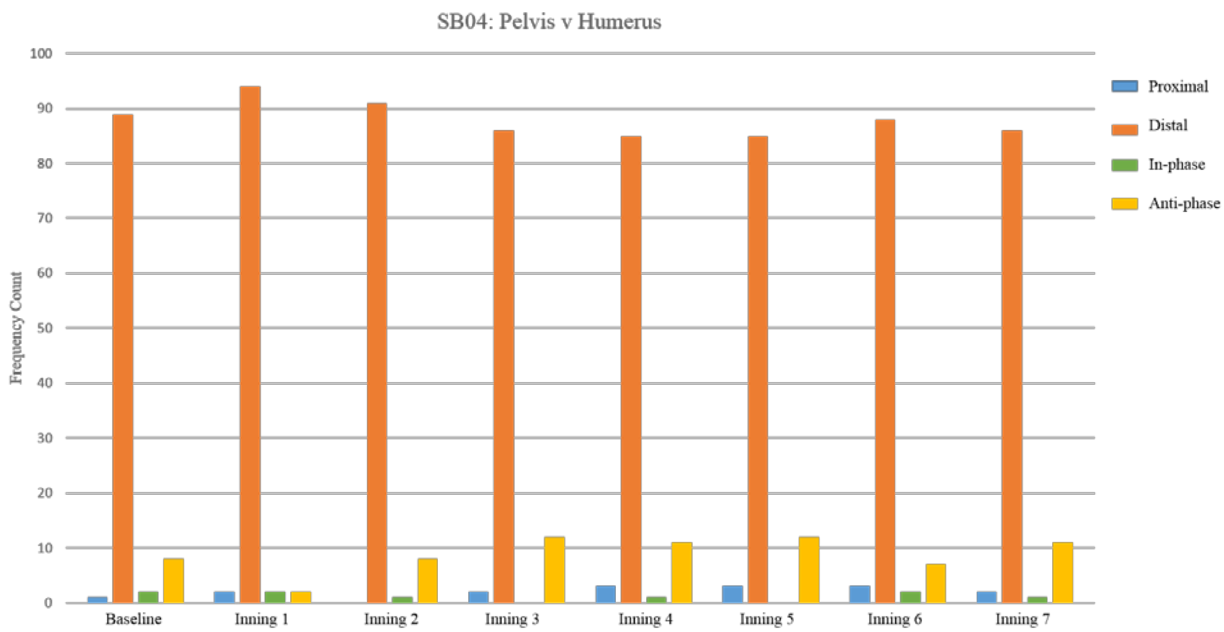


Figure 26. SB04 Pelvis v Humerus coordination pattern frequency counts

Coordination patterns stay consistent over consecutive innings for Pelvis v Humerus (Figure 25). Polar plots illustrate almost total dominance of humerus (distal) coordination pattern, meaning that most motion occurs primarily by the humerus compared to the pelvis.

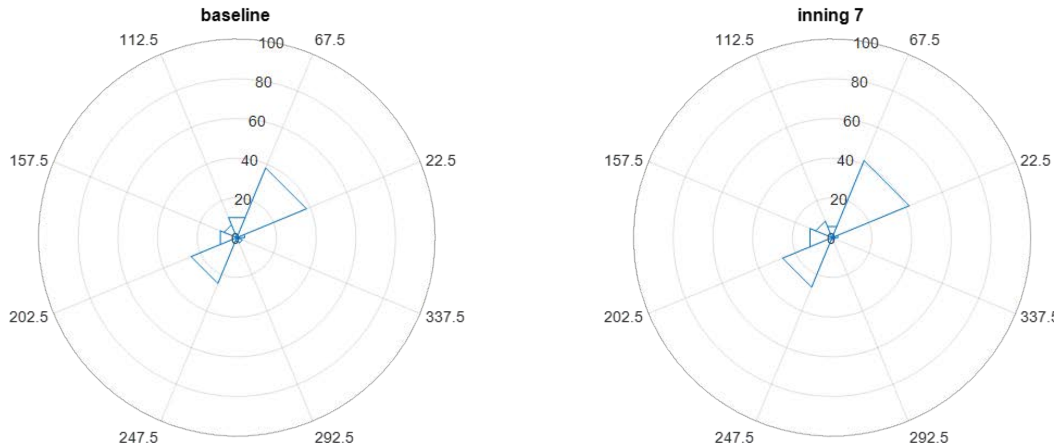


Figure 27. Polar plot of SB04 Pelvis v Torso for baseline and inning 7

Figure 28. SB04 Pelvis v Torso coordination pattern frequency counts

Pelvis v Torso reveals predominant in-phase rotation with a large number of average coupling angles in corresponding bins on opposite sides of the unit circle (Figure 27). In-phase rotation would be depicted by the pelvis and torso rotating together as one unit through the windmill pitch.

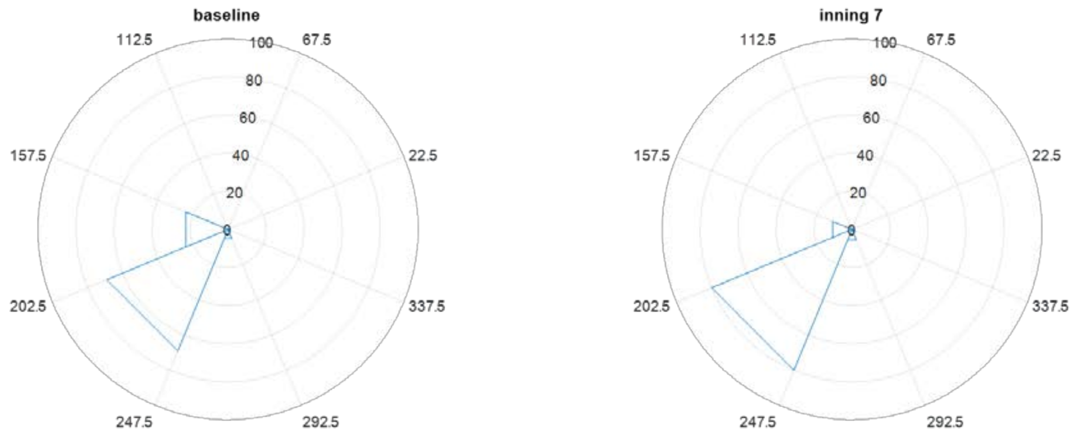


Figure 29. Polar plot of SB10 Humerus v Forearm for baseline and inning 7

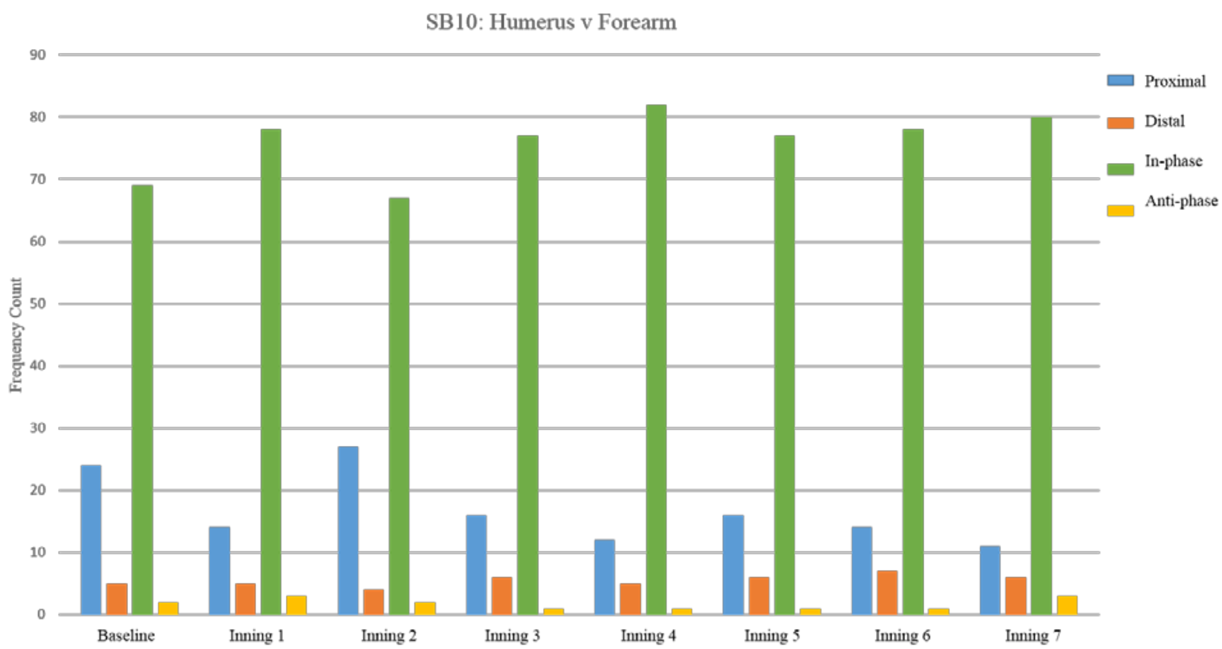


Figure 30. SB10 Humerus v Forearm coordination pattern frequency counts

SB10 Humerus v Forearm displays prevailing in-phase coordination pattern with average coupling angles largely falling between 202.5° and 247.5° (Figure 29).

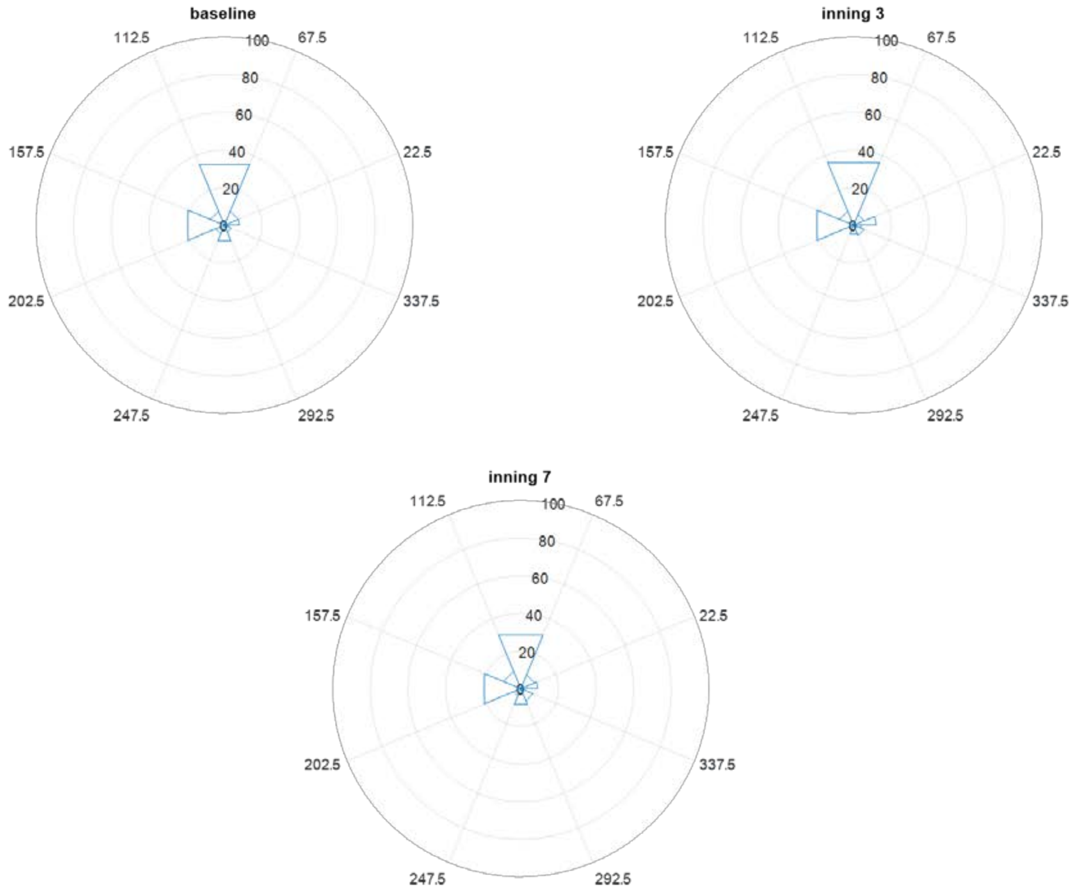


Figure 31. Polar plot of SB10 Drive Leg v Pelvis for baseline and innings 3, 7

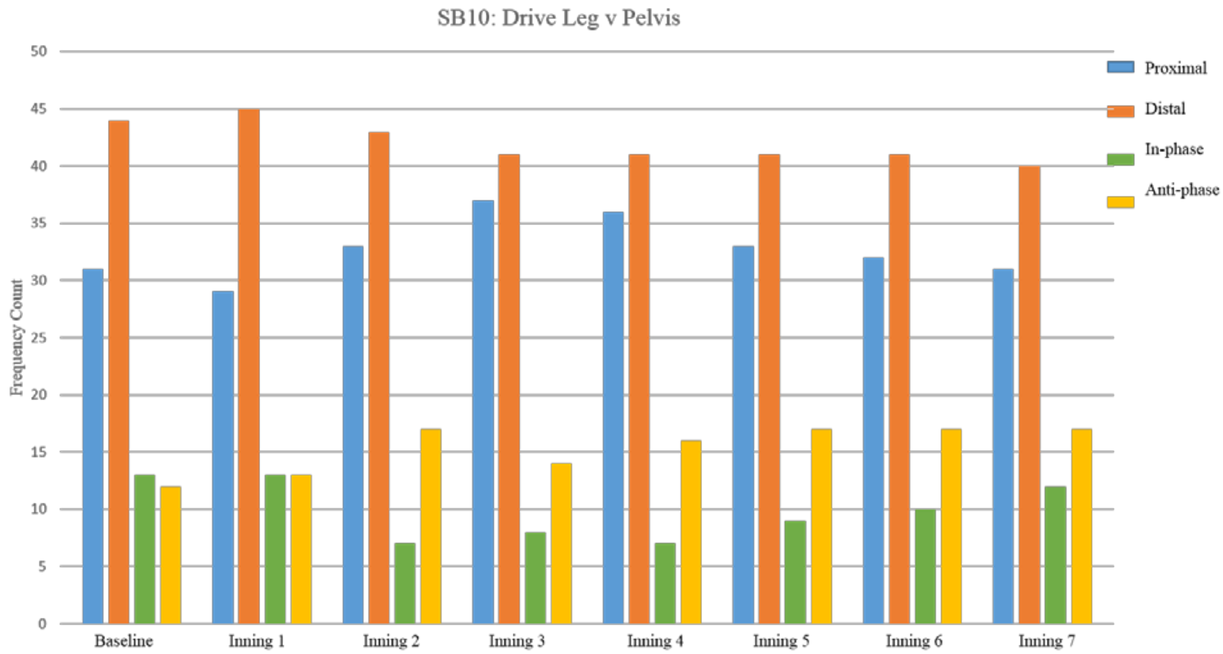


Figure 32. SB10 Drive Leg v Pelvis coordination pattern frequency counts

Similar to SB04, Drive Leg v Pelvis coordination pattern in SB10 fluctuates between innings (Figure 31). Overall, a slight preference for drive leg (distal) coordination pattern, in which motion occurs largely from drive leg flexion and extension.

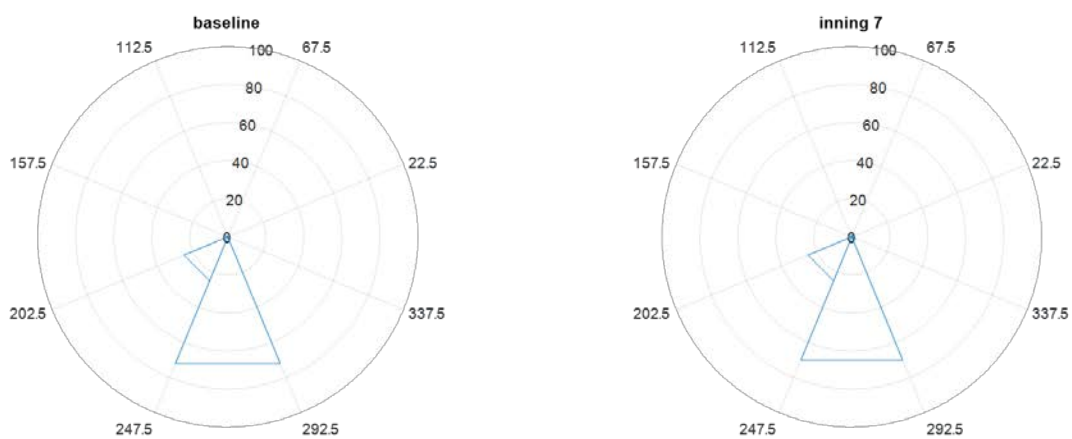


Figure 33. Polar plot of SB10 Pelvis v Humerus for baseline and inning 7

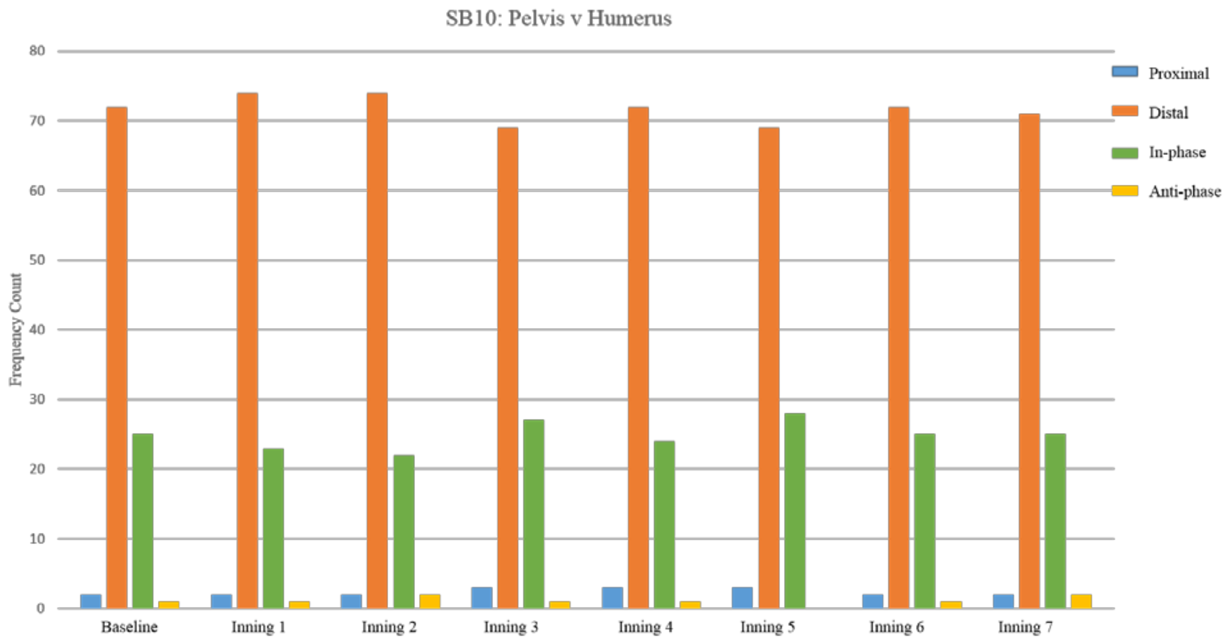


Figure 34. SB10 Pelvis v Humerus coordination pattern frequency counts

Pelvis v Humerus polar plots show a consistent reliance on humerus (distal) dominant coordination patterns throughout all seven innings, observed by average coupling angles around the vertical axis (Figure 33).

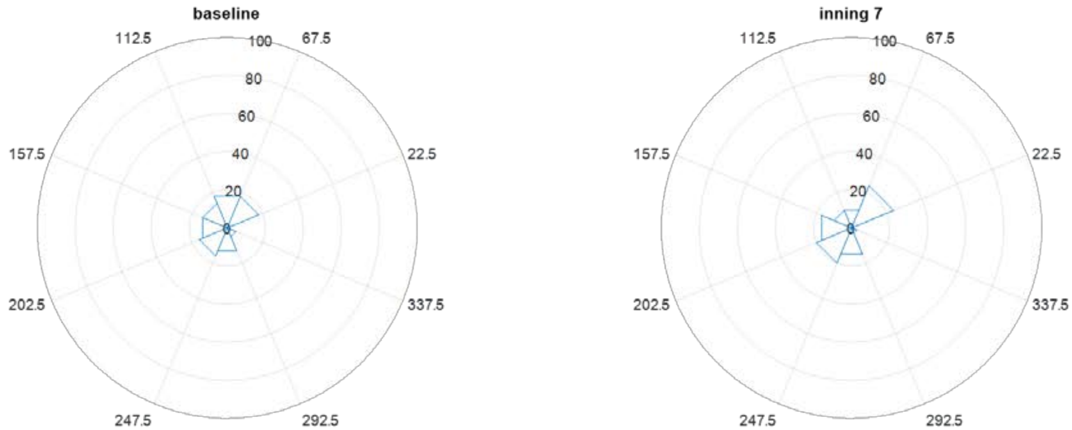


Figure 35. Polar plot of SB10 Pelvis v Torso for baseline and inning 7

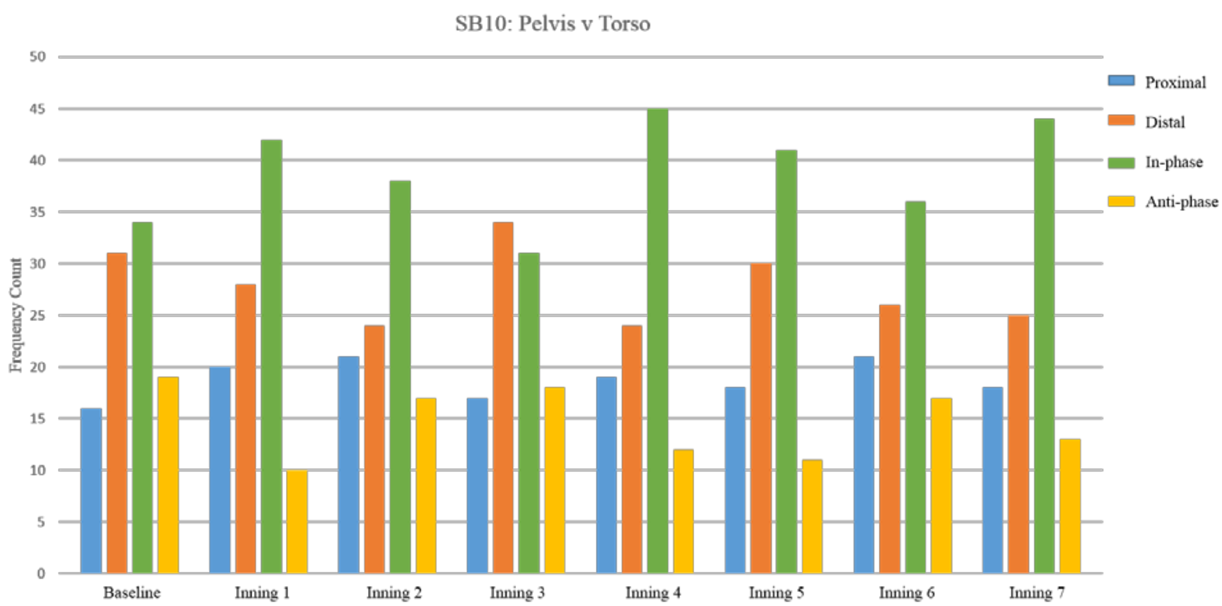


Figure 36. SB10 Pelvis v Torso coordination pattern frequency counts

Pelvis v Torso rotation shows a slight preference to in-phase coordination toward inning 7, where the pelvis and torso rotate in the same direction (Figure 35).

A one way repeated-measured analyses of variance (ANOVA) was used to assess all subjects' change in frequency distribution over innings. No significant differences were seen in coupling angle frequency count within each bin over consecutive innings, Table 4.

Table 4. ANOVA of frequency counts over innings

	Humerus v Forearm		Drive Leg v Pelvis		Pelvis v Humerus		Pelvis v Torso	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Bin 1 (337.5 - 22.5°)	-	-	1.386	0.264	-	-	0.870	0.534
Bin 2 (22.5 - 67.5°)	-	-	0.582	0.655	1.013	0.359	0.511	0.823
Bin 3 (67.5 - 112.5°)	1.953	0.074	0.805	0.586	1.701	0.208	0.503	0.829
Bin 4 (112.5 - 157.5°)	0.225	0.978	1.127	0.356	1.546	0.166	1.345	0.273
Bin 5 (157.5 - 202.5°)	0.158	0.922	0.948	0.476	0.981	0.452	1.355	0.238
Bin 6 (202.5 - 247.5°)	0.985	0.449	1.981	0.070	0.506	0.672	1.419	0.212
Bin 7 (247.5 - 292.5°)	0.181	0.988	1.580	0.156	1.079	0.373	0.669	0.698
Bin 8 (292.5 - 337.5°)	0.656	0.503	1.147	0.315	1.000	0.439	1.063	0.381

- signifies no coupling angles fell within that bin

4.2.1 Variability of coordination patterns

Coupling angles were examined as the average of five consecutive pitches for baseline and each consecutive inning. Average coupling angle and coupling angle variability were plotted across 100 normalized data points, consistent with vector coding protocols, for baseline and select innings of the same two subjects presented above (Figure 38 – 41). Plotted data for all coordinative structures, baseline through inning 7, for the subjects SB04 and SB10 can be found in Appendix E. Plotted data began at the start of Phase 2 and ended with ball release. Figure 37 shows the windmill pitch in reference to the plotted data.

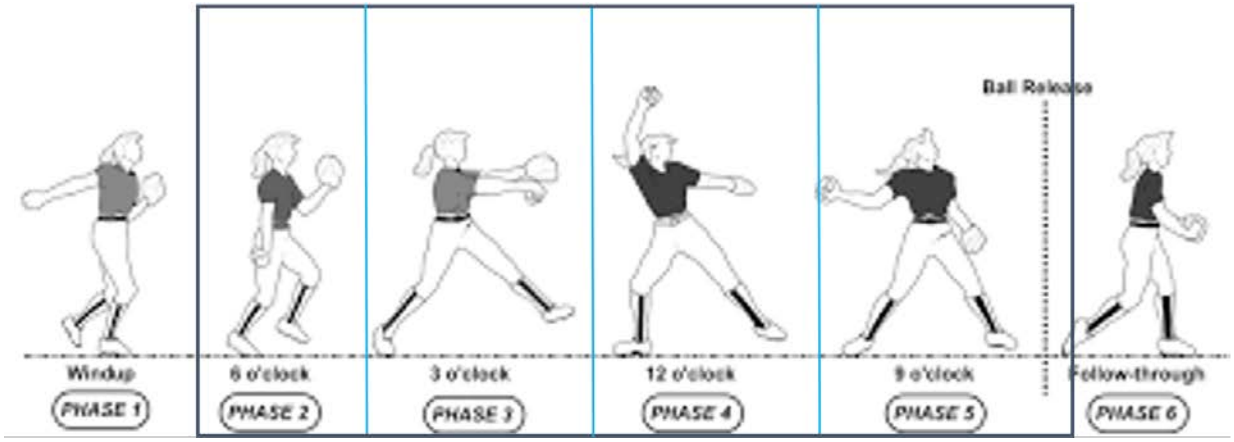


Figure 37. Windmill Pitch Delineations as Plotted Coupling Angles

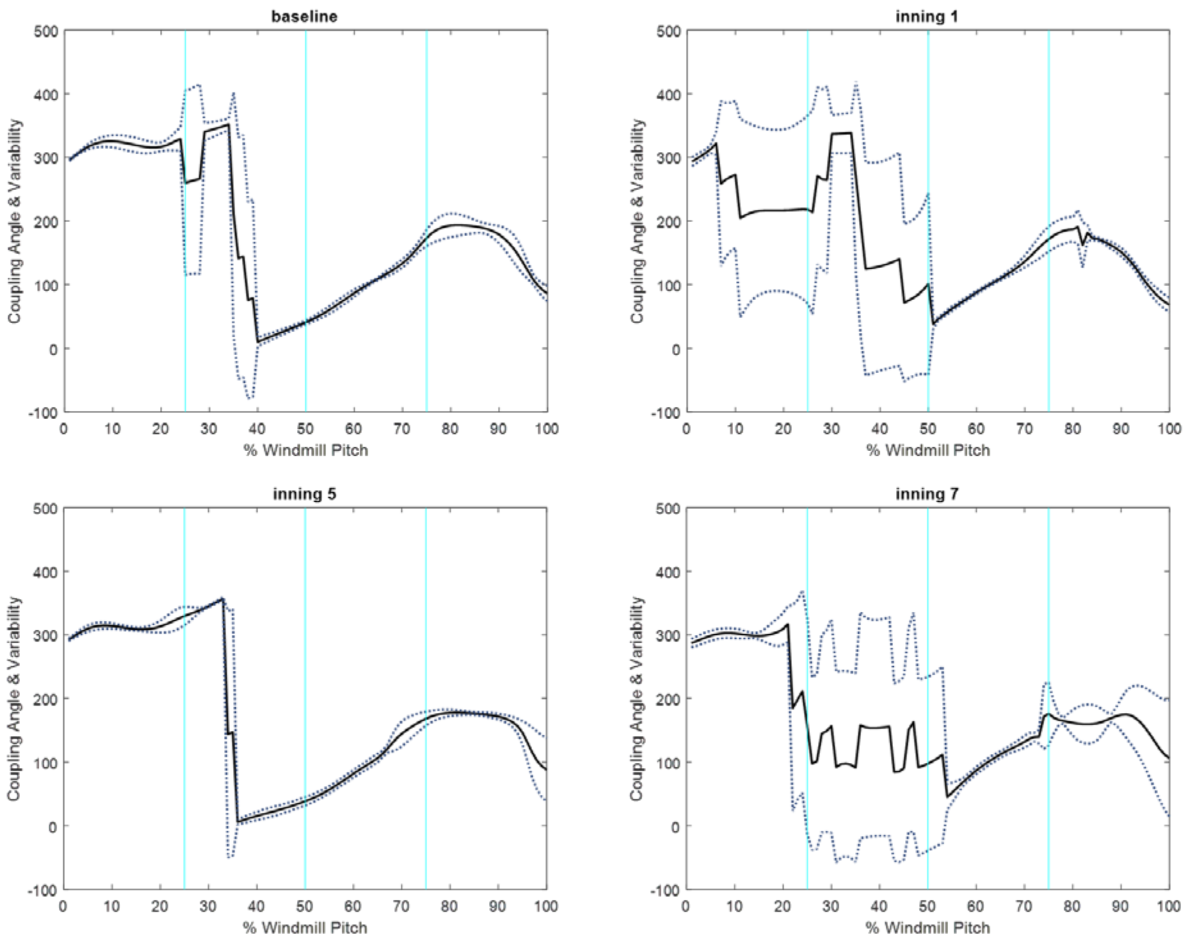


Figure 38. SB04 Drive Leg v Pelvis average coupling angle and variability for baseline and innings 1, 5, 7

Like the fluctuations in coordination patterns, Drive Leg v Pelvis average coupling angle changes through Phase 2 and 3 over innings (Figure 38). Minimal variability is seen during baseline and inning 5, with a change in coordination during the middle of Phase 3. Inning 1 depicts multiple changes in coordination with large amounts of surrounding variability in Phase 2 and 3, with variability significantly decrease for the end of the windmill pitch. Changes in coordination are again seen in Inning 7 during Phase 3 with similar increase in variability. Increases in variability of Drive Leg v Pelvis coordination may allow for another coordinative structure to be tightly controlled during this point. A decrease in variability is seen in Phase 4 of Inning 7 followed by an increase in variability from Phase 5 until ball release.

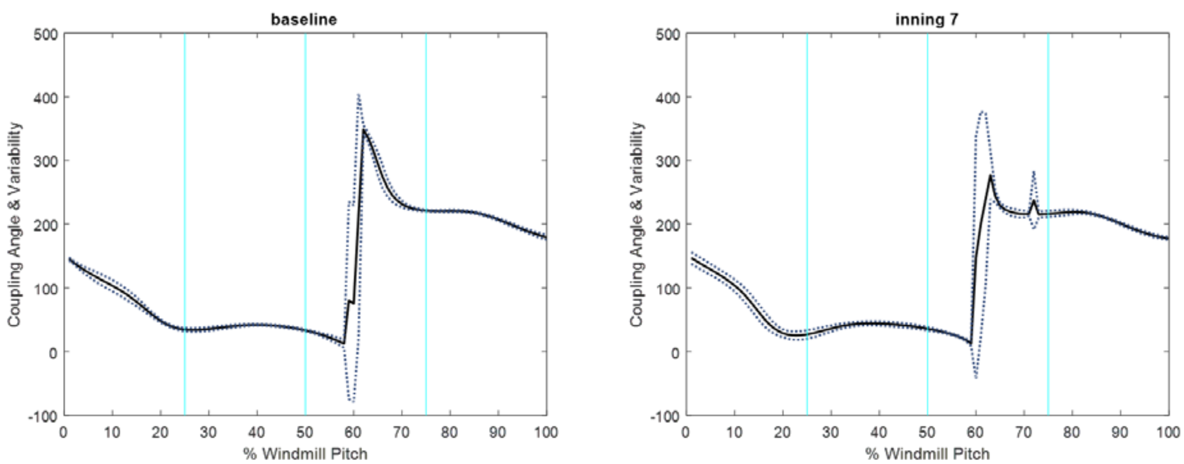


Figure 39. SB04 Pelvis v Torso average coupling angle and variability for baseline and inning 7

Similar to Humerus v Forearm, a change in coordination of Pelvis v Torso is seen in the middle of Phase 4 (Figure 39). Minimal variability is seen over the pitch cycle throughout all innings with a slight increase only around the change in coordination. Minor variability indicates tightly controlled movement between pelvis and torso rotation.

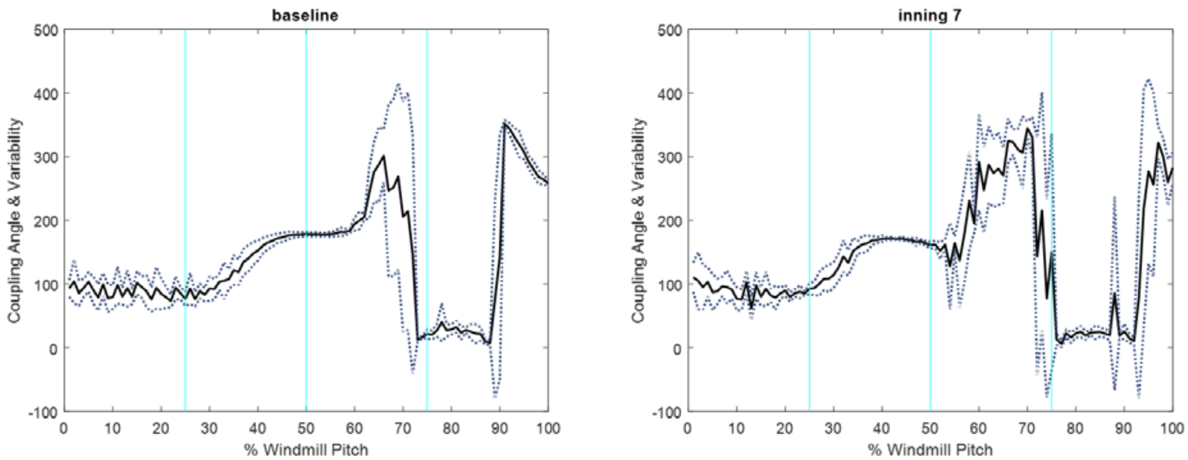


Figure 40. SB10 Drive Leg v Pelvis average coupling angle and variability for baseline and inning 7

Drive Leg v Pelvis coordination remains relatively stable with moderate variability from the beginning of Phase 2 until the middle of Phase 4, where a large change in coordination occurs (Figure 40). Another change in coordination is seen at the end of Phase 5 just before ball release. Variability surround the last half of the pitch cycle is slightly increased by Inning 7, possibly allowing for tighter control over other structures.

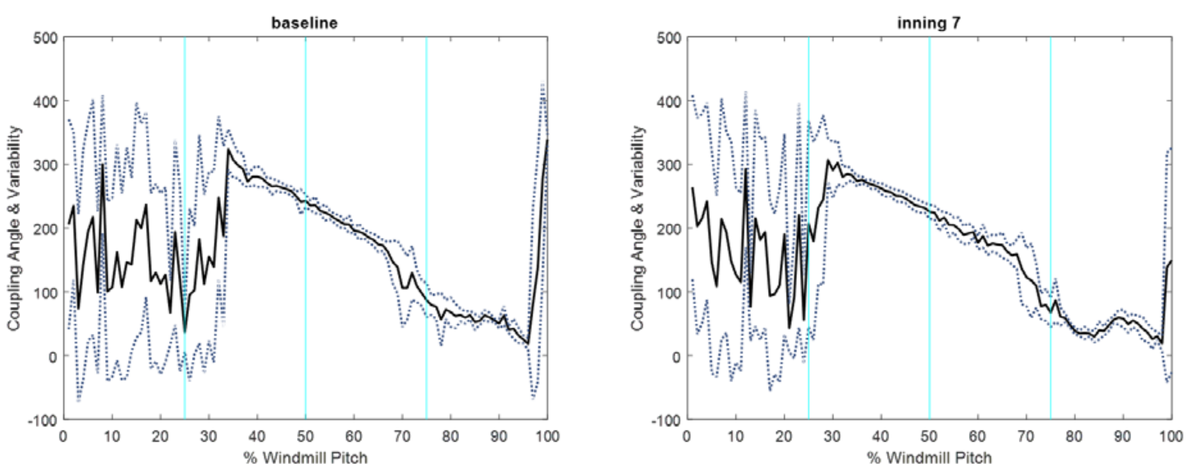


Figure 41. SB10 Pelvis v Torso average coupling angle and variability for baseline and inning 7

Greater variability, is seen in Pelvis v Torso during the beginning of the windmill pitch (Figure 41), which may represent normal modulation of movement to allow tighter control among other variabiles. Variability decreases as coordination becomes stable from the middle of Phase 3 until ball release.

Additionally, pitchers who appeared to demonstrate the least amount of variability (SB05) and most consistent increased variability (SB09) when plotted were compared (Figures 42-45).

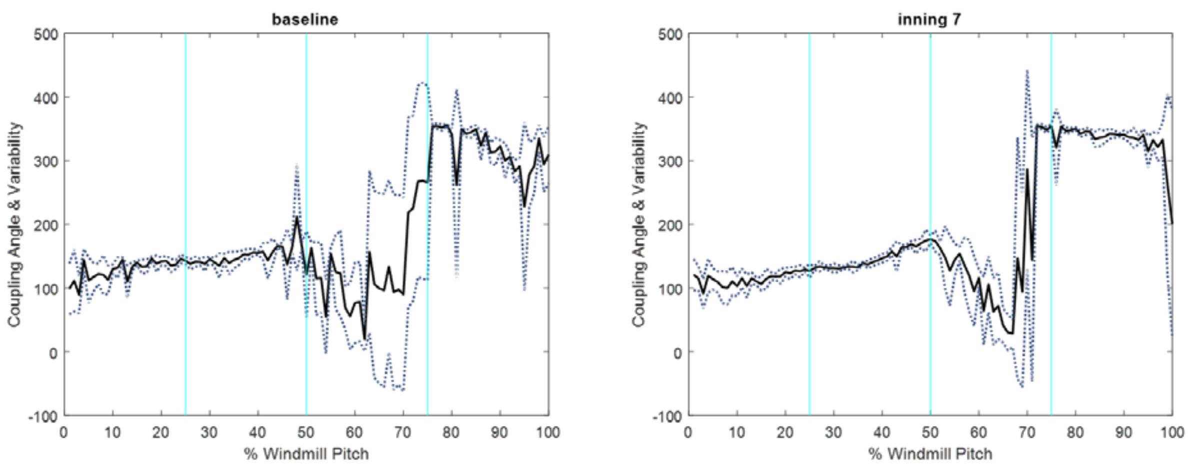


Figure 42. SB05 Drive Leg v Pelvis average coupling angle and variability for baseline and inning 7

Consistent average coupling angle and minimal variability is seen in Phase 2 and 3 of Drive Leg v Pelvis (Figure 42). Opposite of Humerus v Forearm, baseline data shows an increase in variability in the second half of the pitch cycle but decreases to minimal variability by Inning 7.

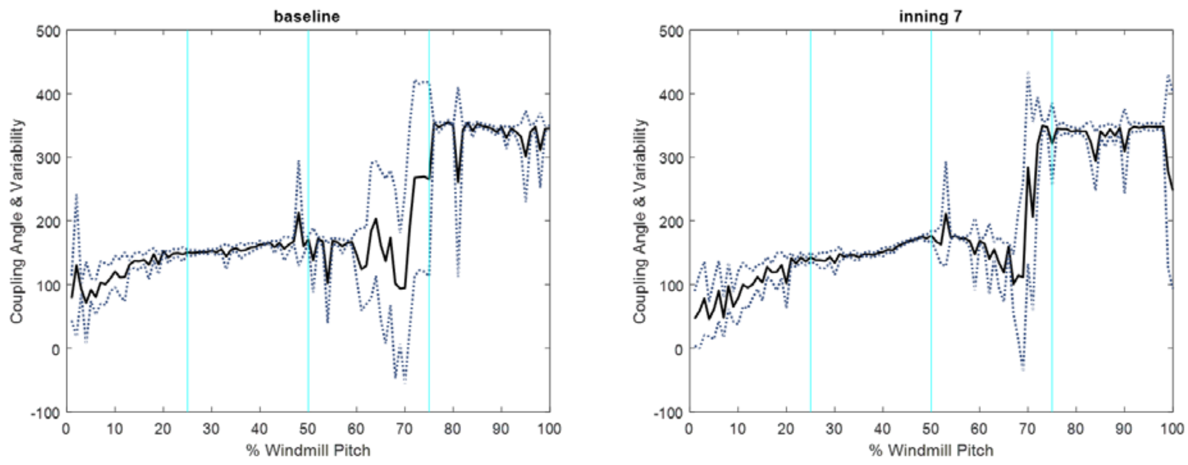


Figure 43. SB05 Pelvis v Torso average coupling angle and variability for baseline and inning 7

Pelvis v Torso coordination follows a similar pattern to Drive Leg v Pelvis, with a change in coordination at the end of Phase 4 combined with an increase in variability (Figure 43). Overall in SB05, minimal amount of variability is seen through Phase 2 and Phase 3 and again from Phase 5 until ball release of all graphed data.

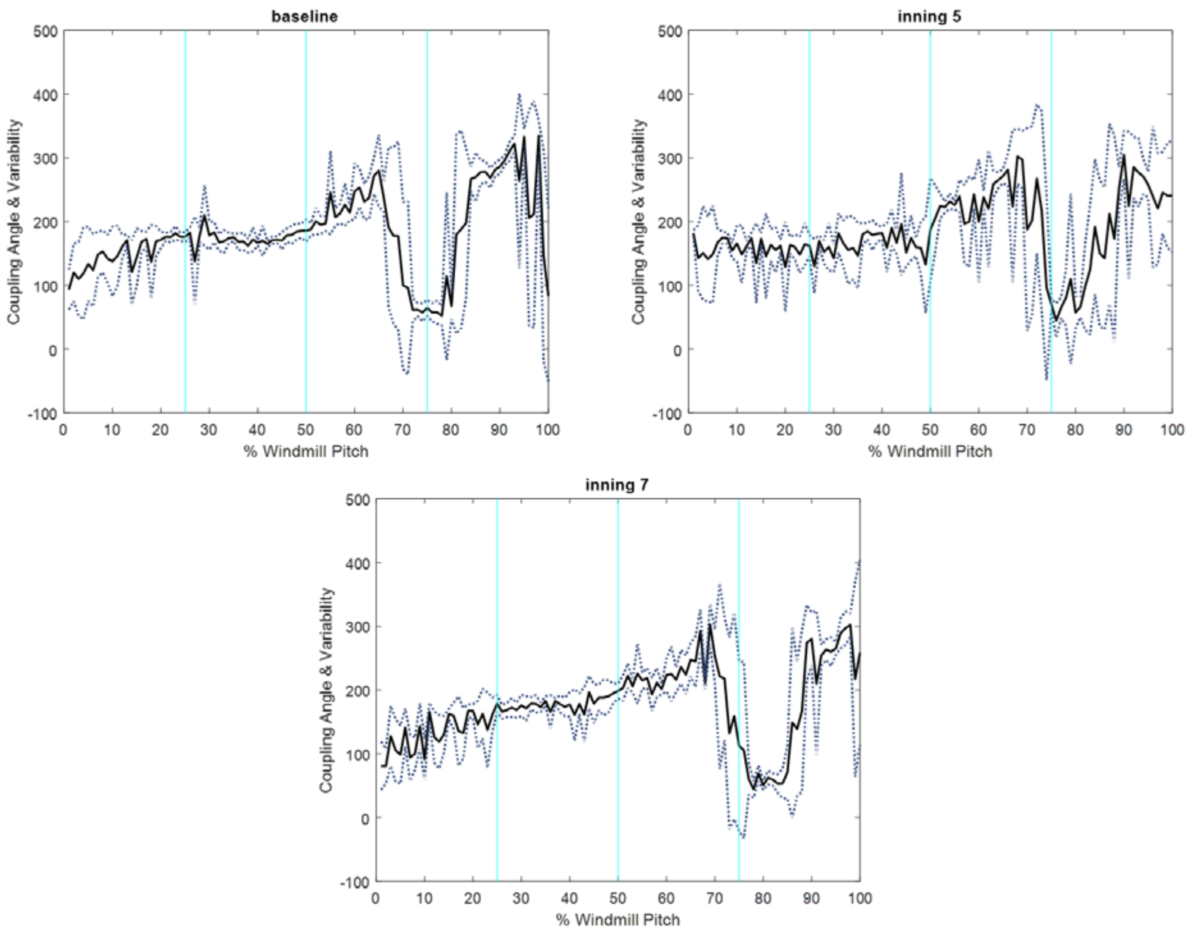


Figure 44. SB09 Drive Leg v Pelvis average coupling angle and variability for baseline and innings 5, 7

As in SB05, a large change in coordination is seen between Drive Leg v Pelvis at the end of Phase 4 additionally, in SB09, another change is seen just before ball release. Variability throughout each pitch cycle indicates less restriction of this coordinative structure, allowing tighter control elsewhere in the body.

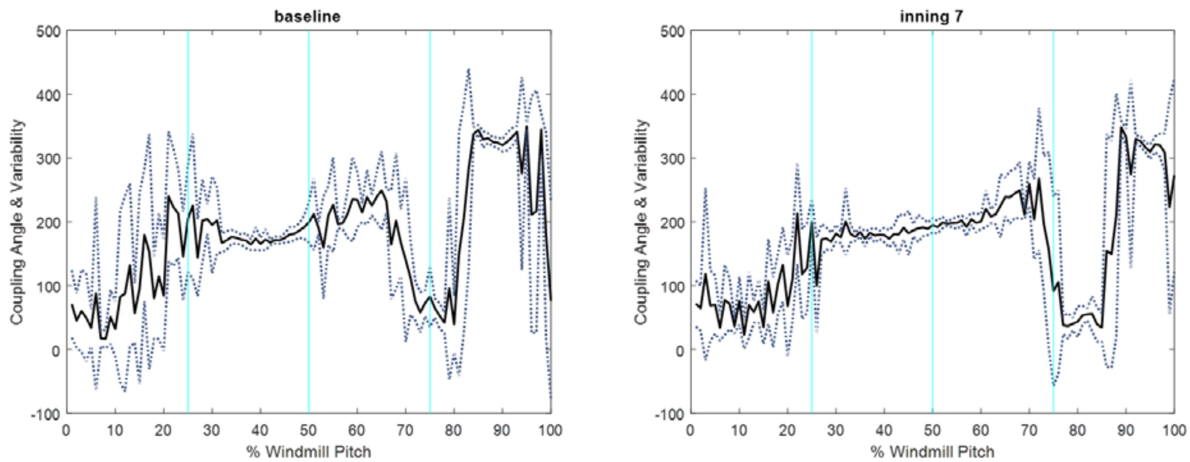


Figure 45. SB09 Pelvis v Torso average coupling angle and variability for baseline and inning 7

Pelvis v Torso demonstrates the largest and most consistent amount of variability of all segment pairs for SB09, with a slight decrease in Phase 3 (Figure 45). Rather than maladaptation, variability seen throughout the windmill pitch may be critical to the stabilization of performance parameters the directly influence pitch velocity and accuracy.

4.3 SPECIFIC AIM 3: COMPARISON MUSCULAR STRENGTH

Normality testing of the change in strength values, using a Shapiro-Wilk test, was completed to determine appropriate testing methods. Comparisons of concentric muscular strength of the knee, hip, trunk and elbow flexors and extensors and trunk rotators at baseline and post pitching of a simulated game were assessed using a paired t-test or Wilcoxon signed ranks tests, as appropriate. Baseline and post pitching strength values are shown as peak torque expressed as a percentage of body weight and time to peak torque for each variable in Table 5. Statistical comparison was completed using a paired t-test unless otherwise noted. The analysis showed that stride leg knee extension peak torque, as percent body weight, was significantly higher post-pitching (M=75.1, SD=24.6) as compared to baseline (M=64.0, SD=19.5), $t(13) = -2.823$, $p = 0.020$ and that trunk flexion peak torque, as percent body weight, was significantly higher post-pitching (M=84.8, SD=47.0) as compared to baseline (M=63.5, SD=47.1), $Z = -2.599$, $p = 0.009$.

Table 5. Comparison of muscular strength values between baseline and post-pitching

	Baseline		Post-Pitching		
	mean (sd)	*median (1Q, 3Q)*	*mean*	*median (1Q, 3Q)*	p-value
Drive Leg Knee Flexion Peak TQ/BW (%)	55.8 (22.0)	49.4 (41.6, 62.1)	55.5 (20.6)	49.2 (42.5, 68.3)	0.934
Drive Leg Knee Flexion Time to Peak TQ	397.0 (118.3)	425.0 (322.5, 482.5)	387.0 (135.1)	425.0 (347.5, 465.0)	0.713
Drive Leg Knee Extension Peak TQ/BW (%)	73.1 (20.1)	70.1 (56.2, 87.0)	73.9 (22.4)	64.3 (58.0, 87.2)	0.772
Drive Leg Knee Extension Time to Peak TQ	218.0 (187.2)	250.0 (17.5, 365.0)	188.0 (170.3)	170.0 (10.0, 360.0)	0.339
Stride Leg Knee Flexion Peak TQ/BW (%)	53.3 (18.1)	51.2 (42.7, 60.9)	55.6 (19.3)	51.8 (40.7, 74.3)	0.589
Stride Leg Knee Flexion Time to Peak TQ	371.0 (167.5)	425.0 (282.5, 497.5)	394.0 (144.5)	450.0 (375.0, 480.0)	0.718
Stride Leg Knee Extension Peak TQ/BW (%)	64.0 (19.5)	59.5 (49.5, 72.2)	75.1 (24.6)	68.8 (53.6, 101.9)	**0.020**
Stride Leg Knee Extension Time to Peak TQ	204.0 (128.5)	190.0 (127.5, 327.5)	224.0 (159.9)	175.0 (115.0, 362.5)	0.811
Drive Leg Hip Flexion Peak TQ/BW (%)	64.5 (31.4)	65.2 (35.3, 86.9)	78.2 (35.7)	72.6 (54.9, 85.8)	0.345
Drive Leg Hip Flexion Time to Peak TQ	271.0 (207.6)	250.0 (87.5, 412.5)	268.0 (78.9)	230.0 (207.5, 350.0)	0.097
Drive Leg Hip Extension Peak TQ/BW (%)	38.8 (10.8)	38.6 (32.6, 45.3)	41.6 (15.6)	40.8 (30.0, 60.0)	0.471
Drive Leg Hip Extension Time to Peak TQ	182.0 (202.7)	50.0 (30.0, 372.5)	225.0 (284.5)	50.0 (32.5, 490.0)	0.732
Stride Leg Hip Flexion Peak TQ/BW (%)	65.9 (35.7)	54.5 (44.3, 83.7)	85.9 (37.9)	79.7 (57.7, 100.7)	0.108
Stride Leg Hip Flexion Time to Peak TQ	324.0 (113.7)	350.0 (217.5, 420.0)	269.0 (108.8)	220.0 (207.5, 305)	0.377
Stride Leg Hip Extension Peak TQ/BW (%)	42.9 (10.4)	46.7 (34.2, 51.8)	45.2 (10.1)	47.4 (35.4, 52.2)	0.579
Stride Leg Hip Extension Time to Peak TQ	169.0 (185.3)	50.0 (30.0, 372.5)	248.0 (276.6)	210.0 (37.5, 340.0)	0.465
Trunk Flexion Peak TQ/BW (%)	63.5 (47.1)	46.8 (25.2, 110.4)	84.8 (47.0)	88.0 (37.0, 127.4)	**0.009***
Trunk Flexion Time to Peak TQ	374.0 (275.6)	400.0 (57.5, 592.5)	497.0 (270.5)	410.0 (330.0, 735.0)	0.285
Trunk Extension Peak TQ/BW (%)	111.9 (100.8)	72.8 (39.7, 186.1)	122.7 (97.6)	94.4 (43.7, 193.0)	0.456
Trunk Extension Time to Peak TQ	444.0 (309.5)	290.0 (22.5, 690.0)	370.0 (321.7)	245.0 (92.5, 670.0)	0.586
Trunk Rotation Toward Peak TQ/BW (%)	75.4 (25.0)	77.7 (53.5, 108.2)	76.2 (30.1)	71.2 (51.5, 90.0)	0.909
Trunk Rotation Toward Time to Peak TQ	328.0 (254.8)	215.00 (172.5, 452.5)	293.0 (194.9)	225.0 (190.0, 310.0)	0.759
Trunk Rotation Away Peak TQ/BW (%)	71.1 (19.3)	74.4 (50.6, 87.4)	72.6 (19.6)	70.4 (51.7, 94.0)	0.797
Trunk Rotation Away Time to Peak TQ	308.0 (251.4)	215.0 (190.0, 290.0)	308.0 (173.5)	235.0 (200.0, 347.5)	1.000
Pitching Elbow Flexion Peak TQ/BW (%)	36.5 (6.4)	36.7 (29.7, 41.7)	33.5 (7.9)	35.2 (23.9, 39.2)	0.256
Pitching Elbow Flexion Time to Peak TQ	330.0 (293.4)	250.0 (65.0, 630.0)	316.0 (250.3)	260.0 (120.0, 452.5)	0.914
Pitching Elbow Extension Peak TQ/BW (%)	31.2 (5.4)	29.9 (27.3, 36.5)	28.9 (6.7)	29.7 (21.9, 33.3)	0.263
Pitching Elbow Extension Time to Peak TQ	360.0 (258.2)	305.0 (175.0, 585.0)	317.0 (216.1)	265.0 (175.0, 592.5)	0.748

mean (standard deviation) — median (1st quartile, 3rd quartile)

TQ = torque — TQ/BW = peak torque as percentage of body weight

*Wilcoxon signed ranks test — **significant at p < 0.05**

4.4 SPECIFIC AIM 4: ASSESS PITCHING PERFORMANCE

4.4.1 Pitching Velocity

Normality testing, using a Shapiro-Wilk test, was completed to determine appropriate testing methods. Pitching performance was defined by average pitch velocity (kph) and pitch accuracy (proportion of strikes), at baseline and within the last 5 pitches of each inning throughout a simulated game. Average pitch velocity per inning is shown in Table 6

Table 6. Average pitch velocity (kph) by inning

Inning	mean (sd)	median (1Q, 3Q)
baseline	72.6 (23.9)	80.0 (75.2, 81.8)
1	80.5 (7.3)	82.0 (77.2, 83.8)
2	80.5 (7.5)	81.8 (76.2, 84.4)
3	80.4 (7.8)	81.6 (76.8, 85.0)
4	79.6 (8.3)	79.8 (77.6, 85.2)
5	79.2 (8.0)	80.0 (77.0, 85.0)
6	79.1 (8.5)	80.2 (77.2, 82.4)
7	79.1 (8.8)	80.2 (77.2, 84.0)

mean (standard deviation)
median (1st quartile, 3rd quartile)

A Friedman one way repeated-measured analyses of variance (ANOVA) was used to assess changes in ball velocity over each inning. There was a statistically significant difference in ball velocity over innings, $\chi2(13) = 18.641$, $p = 0.009$, as seen in Table 7

Table 7. Friedman ANOVA of pitch velocity (kph) across innings

	Chi-Square	p-value
Pitch Velocity (kph)	18.641	0.009

Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.007$. Innings were compared sequentially, ie: average pitch velocity at baseline was compared to inning 1, inning 1 was compared to inning 2. (Table 8). Median (IQR) pitch velocity for baseline and inning 1 were 80.0 (75.2 to 81.8) and 82.0 (77.2 to 83.8), respectively. There was a statistically significant increase in pitch velocity in inning 1 compared to baseline (Z= - 2.749, p= 0.006). There were no significant differences between all other subsequent innings.

Table 8. Pairwise sequential comparison of average pitch velocity (kph)

Inning comparison	baseline_1	1_2	2_3	3_4	4_5	5_6	6_7
p-value	**0.006**	0.937	0.969	0.158	0.384	0.753	0.959

significant at p < 0.007

4.4.2 Pitching Accuracy

Pitch accuracy, as proportion of strikes, mean, standard deviation and median for baseline and the end each inning is shown in Table 9.

Table 9. Average proportion of strikes thrown by inning

Inning	mean (sd)	median (1Q, 3Q)
baseline	0.58 (0.28)	0.60 (0.40, 0.80)
1	0.76 (0.17)	0.80 (0.60, 0.80)
2	0.78 (0.21)	0.80 (0.60, 1.0)
3	0.67 (0.21)	0.60 (0.60, 0.80)
4	0.84 (0.15)	0.80 (0.80, 1.0)
5	0.69 (0.24)	0.60 (0.40, 1.0)
6	0.76 (0.15)	0.80 (0.60, 0.80)
7	0.65 (0.25)	0.80 (0.60, 0.80)

mean (standard deviation)
median (1st quartile, 3rd quartile)

A Friedman ANOVA was used to assess for differences in pitch accuracy across innings. No differences were found between innings, as seen in Table 10.

Table 10. Friedman ANOVA of pitch accuracy across innings

	Chi-Square	p-value
Pitch Accuracy (proportion of strikes)	11.057	0.136

4.4.3 Windmill Pitch Cycle

Average pitch cycle duration, in milliseconds, and maximum stride length, in meters, were calculated for baseline and each inning. Descriptive data for pitch cycle time and stride length can be found in Table 11.

Table 11. Average pitch cycle duration (ms) and stride length (m) by inning

	Cycle Duration (ms)		Maximum Stride Length (m)	
Inning	mean	sd	mean	sd
baseline	384.7	52.0	1.29	0.16
1	392.7	48.6	1.32	0.16
2	410.0	45.3	1.30	0.18
3	404.7	46.2	1.32	0.16
4	415.3	36.2	1.31	0.16
5	420.7	37.5	1.31	0.16
6	421.3	44.4	1.30	0.16
7	405.3	44.3	1.31	0.15

sd = standard deviation

A one way repeated-measured analyses of variance (ANOVA) was used to assess changes in each average pitch cycle duration and maximum stride length. No significant differences were seen either pitch cycle duration or stride length over consecutive innings, as seen in Table 12.

Table 12. Repeated measures ANOVA of pitch duration and stride length

	F-Value	p-value
Average Pitch Cycle Time (ms)	1.41	0.263
Average Stride Length (m)	1.218	0.320

4.4.4 Exertional Measures

Average heart rate were recorded in beats per minute and an OMNI scale rating was taken for the end of each inning. Descriptive data for all heart rate and OMNI scale data can be found in Table 13.

Table 13. Average heart rate (bpm) and OMNI scale by inning

	Heart Rate (bpm)		OMNI scale		
Inning	mean	sd	mean	sd	median
1	116.00	18.95	4.80	0.63	5.00
2	128.17	10.68	4.90	0.74	5.00
3	121.17	13.32	5.00	0.82	5.00
4	126.33	8.12	5.10	0.88	5.00
5	125.83	14.16	5.50	0.97	6.00
6	126.33	10.56	5.40	0.84	5.00
7	130.00	17.46	5.60	0.84	6.00

sd = standard deviation
bpm = beats per minute

A one way repeated-measured analyses of variance (ANOVA) was used to assess changes in heart rate over each inning. A Friedman ANOVA was used to assess for differences in OMNI scale ratings across innings. No significant differences were seen in heart rate over consecutive innings, however the effect of inning was significant in OMNI scale ratings, $\chi2(13) = 28.091$, $p < 0.001$, as seen in Table 14.

Table 14: Repeated measures ANOVA of heart rate and OMNI scale across innings

	F-value	Chi-Square[a]	p-value
Average Heart Rate (bpm)	4.21		0.054
Average OMNI scale rating		28.091	**<0.001**

[a] Chi-squared values reported for Friedman ANOVA results
significant at p < 0.05

OMNI scale post hoc analysis with Wilcoxon signed-rank test was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.007$. Innings were compared sequentially, ie: average pitch velocity at baseline was compared to inning 1, inning 1 was compared to inning 2 (Table 15). There were no significant differences between innings found.

Table 15. Pairwise sequential comparison of OMNI score

Pairwise Comparison of OMNI Score Compared Sequentially						
Inning comparison	1_2	2_3	3_4	4_5	5_6	6_7
p-value	0.317	0.317	0.317	0.046	0.564	0.157

significant at $p < 0.008$

5.0 DISCUSSION

The development of overuse injury in softball pitchers is a constant concern because of the lack of pitching restrictions. Unlike in baseball, a softball pitcher may pitch as many as three consecutive days of double-header 7-innings games in a weekend tournament.[7] Pitchers need to be taught proper mechanics from a young age to master the technique and minimize risk for future injury. Sequential and well-coordinated force development throughout segments of the kinetic chain is essential to maximize force, while simultaneously minimizing internal loads at the joint

The primary purpose of this dissertation was to examine inter-segmental and intra-limb coordination of the softball windmill pitch throughout a simulated game of softball to capture the stability or transitions in coordination due to consecutive pitches. The secondary purpose was to determine if variability surrounding these coordination patterns change throughout multiple pitch counts. Additionally, the difference between pre-pitching and post-pitching concentric, isokinetic strength values were evaluated to determine if muscular fatigue had occurred. Pitch performance, defined as ball velocity and accuracy, was also measured throughout all pitches to determine if any outcome variability occurred. It was hypothesized that increased movement variability in Pelvis axial rotation v Pitching Arm Humerus flexion/extension and Pitching Arm Humerus flexion/extension v Forearm flexion/extension would manifest toward the end of the simulated game to maintain successful pitching outcome. It was hypothesized that there would be a significant decrease in muscular strength of knee, hip, trunk and elbow flexors and extensors and trunk rotators post-pitching of a simulated game compared to pre-pitching strength values. It was also hypothesized that both pitch velocity and accuracy would remain consistent and that ground reaction force vector would increase throughout consecutive pitches.

5.1 SUBJECT CHARACTERISTICS

Fourteen female softball pitchers between 16-23 years of age completed both testing sessions for this study. All subjects identified with the fifth stage of the Tanner scale of physical development. All subjects were currently a rostered pitcher on a high school or collegiate fast pitch softball team and participated in softball related activity for at least 30 minutes three times a week. On average, subjects have the same percentage of years' experience pitching (48.92±6.16 percent of age).

5.2 WINDMILL PITCH COORDINATION PATTERNS

Proper pitching mechanics are critical for the success and health of softball pitchers at any level. Patterns of coordinated behavior arise solely because of the dynamics of the system, with no agent telling the body what to do and when to do it. Development of preferred coordination patterns, or attractor states, allows for highly ordered, stable and consistent movement patterns for specific tasks.[266] To describe this complex system more simply, four coordinative structures were selected to determine if any changes in behavior occurred throughout consecutive pitches.

Coordination patterns of Humerus v Forearm, Drive Leg v Pelvis, Pelvis v Humerus and Pelvis v Torso were examined for any changes throughout consecutive pitches. Average coupling angle and coupling angle variability showed no differences throughout consecutive innings (Table 3). This study utilized a homogeneous group who, on average, use similar movement patterns to execute the windmill pitch over multiple pitches.

Contemporary methodology focuses on group statistical analysis, which allows for generalizability of results. Predictions from a group model reflect the “average” individual.[267] The population of interest for this study is a small subset of a comprehensive athletic population, however, group analysis has the potential to de-emphasize the importance of the individual. Within the Dynamical Systems approach, one-third of the constraints affecting movement are specific to the individual.[81] Different movement strategies result in performance differences that often lead to false support of the null hypothesis,[268] as seen in our results which showed no statistical difference between average coupling angles over consecutive innings. Reliance on group outcome data, represented by a single variable, will provide inadequate characterization of complex coordination solutions used to satisfy constraints. Profiling individual coordination tendencies help with the continuing attempts to understand how different performers seek to satisfy constraints during goal-directed behavior. Average coupling angle and coupling angle variability showed no differences throughout consecutive innings therefore analysis at the individual level was included.

To provide a more detailed examination of coordination, the subject with the slowest pitch velocity (SB04) was compared to the highest pitch velocity (SB10). Coordination profiling examines how each individual satisfies their unique constraints during a goal-directed behavior.[269] The emergence of specific coordination patterns is dependent on the constraints inherent in the task, environment and organism.[270] A consistent difference of Humerus v Forearm coordination was seen between anti-phase pattern of SB04 (Figure 21) and in-phase of SB10 (Figure 29). Examination of polar plots and frequency count distribution shows that both subjects remain in consistent coordination patterns throughout consecutive innings. Moving the humerus and forearm in the same direction, as in SB10 in-phase pattern, allows for a fluid movement and more efficient transfer of energy through the pitching arm to the softball. Similarly, Martin et al.[118] calculated resultant joint forces and torques to determine energy flow during a tennis serve. Their results showed that poor energy flow from the trunk to the hand and racket during the serve limited ball velocity and decreased performance.[118] While future injury was not tracked in this study, poor transfer of energy may cause athletes to create greater loads at the distal ends of movement to offset energy dissipation along the kinetic chain.[271]

Frequency count distribution of Drive Leg v Pelvis relatively even distribution of proximal and distal movement for SB04 (Figure 24) and SB10 (Figure 32) over innings. SB04 also appears have an even distribution of proximal and anti-phase coordination throughout innings while SB10 changes between motion occurring primarily from the pelvis (proximal) or drive leg (distal). Pelvis v Humerus movement consistently remains in phase for both subjects, with SB10 showing more emphasis on distal segment movement. Since constraints on each individual are countless and unique, it would be expected that coordination solutions would differ within and between subjects in order to maintain functionality.[88]

SB04 showed greater patterns of in-phase coordination pattern between Pelvis v Torso (Figure 27), where rotation of each segment occurs in the same direction. Moving as one unit is contradictory to the “x-factor stretch” Cheetham et al.[272] emphasize during the golf downswing, where the hips counter-rotate prior to the shoulders. During the transition to the downswing in n highly skilled golfers, the pelvis slows down and changes direction to rotate forward while the upper body continues to rotate backwards, increasing the x-factor.[273] The “x-factor stretch” is said to elicit the stretch reflex in core muscles, increasing stored elastic energy and allowing stronger muscular contraction.[274] The extra stretch, and active resistance to this stretch, increase the force of muscular contraction and increases force production throughout the windmill pitch. Inability to create dynamic tension in the core when rotating as one unit, decreases the ability to generate optimum power. SB10 shows variation in coordination pattern dominance over innings (Figure 35), which may allow for varying amounts of energy to be stored and then utilized as needed.

Previous work has investigated the effect of fatigue on movement timing after a repetitive, loaded push-pull task (local fatigue) or a lifting task (widespread fatigue).[275] After localized fatigue, subjects made shorter, slower movements and exerted greater control over non-goal-relevant variability, while widespread fatigue caused subjects to exert less control over non-goal-relevant variability and did not change movement patterns.[275] It was thought that fatigue in one segment of a coordinative structure would cause a shift in pitching behavior. No local fatigue may have occurred in our subjects; therefore, no reorganization of coordination was observed over consecutive pitches. This may due to the fact subjects showed no muscular fatigue, eliminating any perturbation to cause change in the system dynamics, or because the most appropriate order parameter for the windmill pitch was not investigated in this study. The addition of batting and outdoor conditions in a real softball game may expedite the onset of muscular fatigue. Polar plots and frequency count distribution gives a summary of coordination patterns over the entire windmill pitch which may hide changes in coordination over one pitch cycle. To assist in finding the most relevant information variables within a complex system, average coupling angle and variability were plotted across 100 time normalized points of the windmill pitch cycle.

5.2.1 Variability in coordination

Dynamical systems approach states there is an inherent variability in all movement patterns that helps individuals adapt to unique constraints.[88] Healthy individuals have a preferred coordination pattern, however, in order for the system to remain unchanged, they also have the ability to vary those coordination patterns in response to perturbations or external conditions.[79] It was thought that potential fatigue could perturb the system dynamics and cause an increase in variability of those segments and decrease at unaffected segments. Average coupling angles appear to vary systematically within the windmill pitch cycle of each individual subject. When average coupling angles were plotted for 100 normalized time points, a change in coordination was often seen in Phase 4 as the pitching arm is brought down from the 12 o'clock position and accelerated in preparation for ball release. An increase in variability was also seen around this change in coordination, likely a subsection of the cyclical performance because it remained constant over innings. When coordinative structures were examined for any changes caused by the scaling up of the suggested control parameter, increasing muscular fatigue due to repetitive pitching, no significant changes in variability were seen.

Subject SB04, with the lowest overall pitching velocity, shows almost no coupling angle variability in Humerus v Forearm (Appendix E.1). Distraction stresses during the windmill pitch have been calculated at 70-98% of body weight at the shoulder and elbow, putting the biceps labrum at risk for overuse injury.[18] Minimal variation in coordination of the upper extremity may accelerate the risk of injury in SB04 by not altering the location of load placed on anatomic structures. Increased variability is seen in SB10 at the start of Phase 2, as the pitching arm moves from 6 o'clock toward 3 o'clock, and decreased in variability during Phase 3 (Appendix E.5). As in SB04, a change in coordination is seen at the end of Phase 4 into the start of Phase 5 with increased variability around this period. Change in coordination may be due to elbow flexion seen during the latter stages of the windmill pitch.[9] Additionally, baseline elbow flexion peak torque was much greater in SB10 (40.1%BW) compared to SB04 (29.7%BW). In both subjects, variability throughout each phase does not appear to fluctuate across innings.

Multiple changes in coordination are seen through the first half of the windmill pitch in SB04 Drive Leg v Pelvis (Figure 38), with the greatest change and largest amount of variability seen around the middle of Phase 3. However, high angular velocities of the hip are seen after this point, during the late delivery phase, as the trunk moves toward the pitching arm,[9] when SB04 demonstrated minimal variability. Changes in coordination and increases in variability were not consistent and did not continually increase over innings. These fluctuations were only seen in Drive Leg v Pelvis of SB04, which may have allowed for consistent coordination and minimal variability in the three other coordinative structures analyzed. Low amount of variability and steady coordination are observed in Phases 2 and 3 of SB10, as body weight is on the ipsilateral leg with the trunk facing forward to body weight transferred forward as the trunk begins to rotate (Figure 40). While SB04 maintains coordination during the end of the windmill pitch, SB10 changes coordination pattern at the end of Phase 4 and regains it at the end of Phase 5 with increased variability seen at initial change in coordination. Changes in Drive Leg v Pelvis coordination of SB10 correspond with the trunk rotating forward as momentum is transferred to the ball prior to ball release.

Similar to Humerus v Forearm of SB04, an initial change in coordination is seen at the beginning of Phase 2 for Pelvis v Humerus (Appendix E.3). Variability increases at this point but immediately decreases to almost no variability for the remainder of the windmill pitch cycle. However, during the later delivery phase, from stride leg contact until ball release, a combination of trunk rotation and arm flexion help accelerate the ball forward resulting in highest magnitude of joint forces.[18] Early change in coordination and overall minimal variability seen in SB04 may decrease her ability to accelerate the ball forward as well as potentially stressing the low back or shoulder complex. Again, SB10 shows increased variability in Phase 2 with a decrease in Phase 3 and most of Phase 4 (Appendix E.7). Variability during Phase 2 and Phase 4 are increased in inning 5 of SB10 but decreases in innings 6 and 7 to similar patterns in early innings.

Coordination of Pelvis v Torso remains consistent from Phase 2 until the middle of Phase 4 in SB04 (Figure 39). A change in coordination is seen in the middle of Phase 4, as the body rotates toward the pitching arm, and then remains stable through ball release. Minimal variability of Pelvis v Torso coordination is seen in SB04 over the entire pitch cycle for all consecutive innings. Lack of variability may affect the amount of energy transmitted through the trunk, as maximal pelvis rotation occurs from 50-75% of the windmill pitch cycle, followed by maximum torso rotation velocity.[18] SB04 may also lack muscular strength needed, as baseline peak torque values were lower for trunk flexion (22.4 vs. 77.5%BW), extension (42.8 vs. 73.2%BW), right (38.4 vs. 99.4%BW) and left rotation (35.8 vs. 99.3%BW). SB10 shows multiple changes in coordination at the beginning of Phase 2, which is also the most dramatic variability seen in all coordinative structures (Figure 41). In the middle of Phase 3, variability minimizes for the reminder of the pitch cycle. These early increases in variability may have been a result of or counteracted by other segment movement patterns, allowing any potential errors in the movement system to be managed.[91]

Nonlinear theories, such as dynamical systems, emphasize healthy disequilibrium, that a system never settles into a stable state, allowing adaptations to change.[276] Reduced variability may not be a mechanical problem but also a results of an information problem. Sensory and motor neural maps are more complex when movement variability is present, contributing to the neuroplasticity needed for maintaining functional skill.[277] Most concerning may be the lack of overall variability seen in SB04. Low variability may be a product of pathological state, even if the subject doesn't report pain during pitching, or could lead to eventual overuse injury.[95] Because SB04 demonstrates a lack of variability in all coordinative structures, it may also be due to a lower skill level,[188] instead of tightly controlled coupling for successful performance. In all coupling angles, limited variability is seen in SB10 from the start of Phase 5 until ball release. This trend may be indicative of her ability to exploit multiple degrees of freedom during the powerful of the drive leg then restrain distal movements to consistent coordination patterns just prior to ball release. Similarly, controlled coupling between the elbow and wrist angles has been proposed as the mechanism determining success of free-throw shots in experienced basketball players.[278]

In addition to evaluating coordination and its variability in terms of the worst (lowest ball velocity) and best performing pitcher (highest ball velocity), coordination was assessed in terms of the smallest overall amount of variability and the most consistently variable. The implication in non-linear dynamics that that the variable that changes qualitatively is the one most relevant to the system, even when overall behavior is smooth.[279] Another approach to determine the best order parameter to summarize the windmill pitch was to look at two subjects who differed in coupling angle variability. Compared to all subjects, SB05 has the least amount of coupling angle variability, yet the most variability in pitching velocity. SB09 has variability patterns that remain consistent throughout the windmill pitch cycle. Consistent with SB04 and SB10, both subjects also show a change in coordination with increase in variability during Phase 4.

Of the four coordinative structures assessed, Humerus v Forearm shows the earliest cycle variability for SB05 (Appendix F.1). Largest variability in SB09 is seen around the change in coordination during Phase 4 (Appendix F.5). Humerus v Forearm variability decreases in Phase 4 in innings 6-7 but increases during Phase 2 and 3 of these final innings. Notably, SB09 showed an increase in elbow flexion peak torque (12.4%BW) after pitching compared to the decrease in SB05 (7.6%BW). Higher strength may afford the ability to vary coordination without stressing static structures of the elbow, by maintaining stability due to muscular strength. Minimal variability of SB05 Drive Leg v Pelvis (Figure 42) and Pelvis v Humerus (Appendix F.3) coordination is seen in Phases 2-3. An increase in variability accompanies a change in coordination at Phase 4, before reducing variability at the end of the pitch cycle. Previous studies suggest decreased variability is attributed to less flexible coordination, indicating less adaptability to changes in the environment.[280] However, results from this study don't allow clear differentiation from decreased variability due to highly constrained coordinative structures to maintain successful outcomes. SB09 increases overall Drive Leg v Pelvis variability over innings 2-5, yet variability during Phase 3 remains minimal across all innings (Figure 44). Again, SB05 exhibited minimal variability over pitch cycle throughout innings for Pelvis v Torso coordination (Figure 43). Smaller amounts of variability around changes in coordination of Pelvis v Torso may indicate a more rigid, Overall minimal amounts of coordination variability seen in SB05 may put her at risk for overuse injuries due to cumulative micro trauma associated with repeated low magnitude impacts applied over a long time period.[94] Large amounts of variability are seen in Phase 2 of SB09 Pelvis v Torso followed by a decrease in variability during Phase 3, which could be a functional exploration in the beginning of the windmill pitch cycle (Figure 45). Change in coordination of SB09 Pelvis v Torso shifts from the end of Phase 4 at baseline toward ball release by the end of all consecutive innings. Interesting to note, in this comparison SB05 had higher average pitch velocity in each inning compared to SB09. This comparison is opposite of previous literature, which states that expert performers typically demonstrate higher coordination variability, that allows flexibility to adapt to perturbations, compared to low variability seen in intermediate performers.[235] This may indicate the amount of variability seen in SB09 are too great and cause destabilization of performance parameters without causing a shift in behavior.

Although there were subject specific differences in the timing of peaks in variability during the windmill pitch, consistent trends were noted across participants. For all subjects, a change in coordination pattern was seen during Phase 4 as the trunk and pitching arm rotate toward the drive leg and the pitching arm begins to accelerate forward. Variability surrounding change in coordination may allow softball pitchers the ability to utilize slightly different movement patterns based on the transfer of kinetic energy to this point. If transfer of momentum is not efficient, the pitcher is afforded the opportunity to a marginally alter coordination. Subjects used in this study were similar in age, height, weight and muscular strength. Yet small differences in these organismic constraints may support the differences in coordination and variability seen.

5.2.2 Clinical application

All subjects in this study were asked to complete the exact same task in the exact same environment. However, coordination patterns and variability were different between all subjects indicating the need for individualized training and the allowance to create their own movement patterns best suited to their constraints. Results of this study show there are many possible coordination patterns in throwing the same windmill style fastball. The process in creating individualized coordination patterns involve modifications from trial to trial.[79] The process of random exploration eventually results in the appropriate solution for a specific task, given the instantaneous constraints in the individual.[83] Highly directed coaching may force individuals to perform using patterns not ideal for their specific constraints. Additionally, the coach is only giving knowledge suitable for that exact instant. Successful movement patterns are then strengthened in the neural pathway by connecting coordination with positive outcomes.[281]

Coaches should encourage a player to evaluate their own performance, continuing to refine their skill. If future research determines an order parameter that best encapsulates the windmill pitch, coaches can focus on that specific phase or movement within the windmill pitch. If Drive Leg v Pelvis is found to be the best order parameter, a coach can assist their pitcher in varying their drive leg push off with the timing of rotating their hips. Through trial and error on the part of the pitcher, she may find a better suited timing strategy that allows more efficient use of energy. Additionally, exercises that incorporate this specific movement can be included in softball practice in ways that don’t include repetitive pitching. Drive leg plyometric or hip mobility exercises are different tasks that may elicit a more effective coordination pattern that can be transferred to the windmill pitch. If muscular fatigue is found to influence coordination patterns, pitching drills can be added to the end of practice of after a conditioning session.

5.3 MUSCULAR STRENGTH

Pitchers who compete in a fatigued state are at a 36-fold increased risk of injury,[59] likely increasing the repetitive stress magnitudes on the pitching arm. The softball windmill pitch is traditionally defined by movement and position within the sagittal plane.[18] Therefore, upper and lower body and torso flexion and extension and torso rotation strength were assessed at a baseline value and after throwing consecutive pitches. A trend of greater peak torque, as a percent of body weight, was seen after pitching for muscular strength assessed except for elbow flexion and extension strength. Significant increases in stride leg knee extension and trunk flexion strength, defined as peak torque as a percent of body weight, were seen after throwing consecutive pitches (Table 5). These results did not fully support the hypothesis. One explanation for an increase in strength, although not evaluated in this study, is the ATP-PC system which is highly responsible for production of energy produced in softball pitching.[101] Energy stores from this system are exhausted in less than 10 seconds, the work to rest ratio is approximately 1:12 for recovery.[282] With only one second of activity per pitch, the 4-minute rest between simulated innings and the time between completion of pitching and beginning of strength testing may have allowed for adequate replenishment of energy stores. Increasing muscular strength may be a necessary adaption because their body is conditioned to pitch for at least twice the number of pitches thrown in this study. This strength allows a softball pitcher to maintain dynamic control of the windmill pitch and consistent performance essential for her sport.

Isokinetic strength testing speeds were based on previous literature that used sport specific speeds on an athletic population. However, the higher speed used during this study may not have been a true representation of maximal muscular force. The force-velocity curve depicts an inverse relationship: as speed of concentric movement increases, fewer number of cross-bridges can attach decrease the force that's able to be produced.[283] For example, a one repetition maximum squat would produce high levels of force but at a slow velocity, while a countermovement jump is executed at high velocity but produces low levels of force. A lower isokinetic test speed may have elicited slight changes in muscular force production that were not able to be detected at a high velocity.

This study assessed strength by groups of joint flexors, extensors and trunk rotators rather than individual muscles. Our results differed from a study of high school fast-pitch softball pitchers, which found significant decreased supraspinatus, forward flexion and external rotation strength was seen after pitching a single game (89 ± 25 total pitches).[237] Similarly, decreased muscular hip and scapular muscular strength was seen in softball pitchers after pitching in a single game (99 ± 21 pitches).[97] Partially similar to our results, Oliver et al.[284] found a significant decrease in non-throwing side hip internal and external rotation pre versus post-game exposure of collegiate pitchers. Although they did not find a difference in hip abduction or adduction strength.[284] All of these studies isolated individual muscular strength by using a handheld dynamometer instead of an isokinetic dynamometer.

Similar to our results, no significant changes in concentric knee flexor and extensor strength was seen after a 90-minute soccer-specific intermittent treadmill protocol.[50] Local fatigue may result in greater muscle imbalances between opposing muscle groups[285] and greater changes in neuromuscular coordination.[286] No changes seen in this study in coordination over consecutive windmill pitches may be due to lack of decrements in muscular strength, as assessed by muscle action groups.

Additionally, no differences were seen in heart rate at the end of consecutive innings (Table 14). At maximum, subjects in this study only reached approximately 65% of their age-predicted heart rate maximum during pitching. This signifies that pitchers in this study were efficient at using energy for activity and did not need the additional oxygen supplied to muscles through increased heart rate. While there was a significant difference in OMNI scale scores over innings (Table 14), on average, reported exertion score was a 5 on a scale of 1-10. OMNI scale scores are a subjective measurement based on the subject but has been correlated with VO_2max in a female adult population.[287] Muscular fatigue may develop after a larger amount of consecutive pitches, but it is difficult to determine how many pitches can be thrown before fatigue sets in and injury risk increases. Muscular fatigue is very individualized, both subjective and objective, and depends on many factors, such as overall conditioning and specificity of training, rest duration between innings and games and cumulative stress to the musculoskeletal system throughout the course of a season.[12]

Instabilities in coordination are created by control parameters, muscular fatigue, that move the system through different patterns characterized by an order parameter. Qualitative change induced by a control parameter is needed to identify the correct order parameters.[279] In this study, the correct order parameter to describe the behavior of the windmill pitch “system” may not have been selected. Results showing no decrease in muscular strength after pitching may also conclude that pitchers in this study were not fatigued enough to perturb the system to allow us to adequately identify the best suited order parameter.

5.4 PITCHING PERFORMANCE

Successful pitching performance is a result of precise timing and coordination of body segments. As seen in the multiple coordination patterns of subjects in this study, the complex nature of movements involved in the windmill pitch are difficult to quantify due to the differences in anatomical, neuromuscular and physiological characteristics in each individual.

5.4.1 Pitching Velocity

Changes in temporal parameters may indicate efficient transfer of momentum during the windmill pitch. No significant changes in coordination or variability were seen in this study, resulting in general maintenance of average pitch velocity throughout the simulated game (Table 7). Statistical differences were found between baseline (72.6 kph) and inning 1 (80.5 kph). Although subjects warmed up and threw practice pitches from full distance before data collection began, average pitch velocity of the first 5 pitches collected was noticeable lower than the second slowest inning (79.1 kph). Average pitch velocity seen by subjects in this study were lower, 79.8 ± 8.0 kph, than those previously seen in youth, 88.5 ± 4.8 kph,[7] and Olympic pitchers, 96.6 ± 8.0 kph.[9]

Increased pitch workload (innings and pitches thrown) has been associated with diminished ball velocity in collegiate baseball pitchers,[56,288] which has been suggested as a protective mechanism. Maintained ball velocity in this study was expected, however it is different from previous research examining the impact of a simulated game on baseball pitchers. As adolescent baseball pitchers progressed through a simulated game, they threw lower velocity pitches (73 ± 5 mph to 71 ± 6 mph).[34] Similarly, collegiate baseball pitchers threw at a significantly lower velocity in the last two innings pitched (33.7 ± 1.5 m/s) compared to the first two innings (34.7 ± 1.8 m/s).[56]

5.4.2 Pitching Accuracy

This is one of the first studies to consider pitching accuracy as a measure of pitching performance. Pitching accuracy was assessed by the proportion of strikes thrown out of the last 5 pitches per inning (# strikes / 5 pitches). As hypothesized, no significant differences were found in the proportion of strikes thrown at the end of each inning throughout a simulated softball game (Table 10). McElwee[289] examined the speed-accuracy tradeoff in the windmill fastball and change-up pitch, with accuracy defined as the score on a target subjects pitched at. No significant correlation was found between the fastball (r= 0.20) or change-up (r= -0.21).[289] The relationship between baseball pitching error and balance was previously studied in a collegiate population. It showed a negative correlation between vestibular-input, measured on the NeuroCom, and pitching error.[290] Both of these studies looked at a limited number of pitches that would represent one inning of a game, not how values may change over time.

5.4.3 Windmill Pitch Cycle

This study found no significant differences in pitch cycle duration or stride length over consecutive innings (Table 12). Werner et al.[7] calculated the time interval from top of backswing (Phase 4) until stride foot contact in youth pitchers as 45 ± 19 milliseconds and from stride foot contact until ball release as 117 ± 17 milliseconds. In Olympic pitchers, time interval from top of backswing until stride foot contact was been reported as 50 ± 16 milliseconds and 100 ± 17 milliseconds from stride foot contact to ball release.[9] These findings averaged out to 162 milliseconds in youth and 150 milliseconds in Olympic pitchers, from Phase 4 until ball release, while this study looked at the duration from Phase 2 until ball release (460 milliseconds).

Youth softball pitchers' stride length has been reported as 103 ± 10cm (1.03m),[7] which is slightly shorter than findings in this study (1.31m). In baseball pitchers, a decreased stride length was seen over consecutive pitches while peak and average ball velocity was maintained.[291] These lower extremity compensatory motions were not found in this study, while pitch velocity was maintained. It was found that shortened strides reduced pitching heart rate, pitching intensity and end of pitching heart rate while improving recovery capacity.[291] Heart rate was maintained throughout consecutive innings in this study, therefore subjects may not have needed to alter stride length due to overexertion.

5.5 LIMITATIONS AND FUTURE RESEARCH

The current study has some limitations worth noting. A healthy, female population with full maturation status was used in this study, therefore results cannot be extrapolated to a prepubescent population. Data collection was conducted during the softball off season, as to not interfere with subject's training. The cumulative effects a competition season may have on a pitcher could have produced different results than found in the current study. Due to space restraints, the distance was 3.96 meters (13 feet) shorter than a regulation infield. A change in start position from home plate (target) may have altered subjects' biomechanics or force in which they drive forward. Pitch accuracy may have also been affected by an increase in distance.

Another limitation may be that pelvis and torso segment motion was calculated relative to the global coordinate system instead of each other. The impact of this method should be limited due to the fact there appears to be limited flexion/extension or abduction/adduction of the pelvis in relation to the global coordinate system. This study may not have included the order parameter most effected by consecutive pitching.

Future research may look at the comparison between pre- and post-pubescent softball pitchers to determine if there is a change with maturation status. Additionally, a whole-body ecologically valid fatiguing protocol could be put in place to ensure fatigue and then determine if any changes in coordination occur. While it was thought that subjects in this study were not fatigued enough to demonstrate changes in coordination patterns or increased variability, different or additional coordinative structures may be assessed in future research. Continued research should also examine individual muscle pre- and post-pitching strength using a handheld dynamometer instead of evaluating muscle groups. Subtle changes in muscular strength may be able to be detected on an individual basis where an assisting muscle cannot help compensate.

The current study was to determine a baseline overview of the demands of one softball game on a pitcher. Forthcoming research should also look at similar variables over the course of a school year; starting with fall ball and practices and continuing through the competition season and post season.

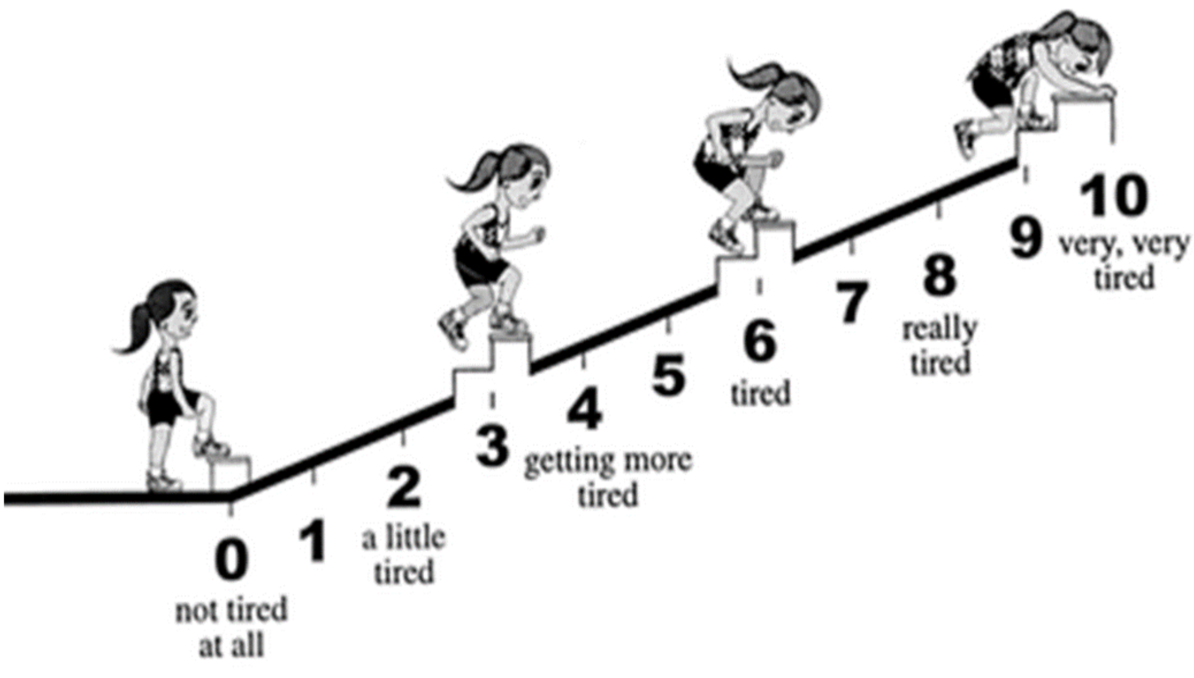
5.6 CONCLUSION

The softball windmill pitch is a complex motor skill that involves numerous interacting components or degrees of freedom. Mastery of these degrees of freedom results in stable, coordinated pitching. Coordination can therefore be defined as the organization of degrees of freedom to produce a functional movement pattern. These patterns of coordination, not individual neuromuscular and biomechanical variables, may provide more insight into the performance of the windmill pitch. The purpose of this study was to describe coordination patterns and its potential variability throughout consecutive softball windmill pitches. Additionally, changes in muscular strength from baseline to post-pitching were assessed as well as pitching performance throughout multiple pitches. Identifying how modifiable measures change over exposure to a single game provide knowledge into potential deficits that occur throughout the course of competition.

Coordination patterns are selected through self-organization to find the most efficient movement within the contest of constraints.[208] Behaviors can be defined through order parameters relative to the motion described, however this study did not evaluate the order parameter that would best describe the softball windmill pitch. No consistent increase in variability found within any coupling angles evaluated in this study, which supports that there were no large changes in coordination patterns throughout innings. Results of this study did not show any significant decrease in either concentric muscular strength or time to peak torque, however there was a significant increase in stride leg extension and trunk flexion peak torque, as percent of body weight, post-pitching. A general decrease in amplitude of force production is a common index of the impact of fatigue, but it fatigue can also be characterized by systematic changes in motor variability.[292] Results of this study indicate that exertion was not great enough to induce muscular fatigue to cause changes in strength or coordination. Finally, no changes were seen in pitch velocity or accuracy over multiple simulated innings. This is one of the first studies to investigate whole body coordination during the softball windmill pitch and associated measures of performance. While this study did not demonstrate the negative effects of consecutive pitching that were expected, results can provide a foundation for future research into windmill pitch mechanics to assist with injury prevention and performance optimization.

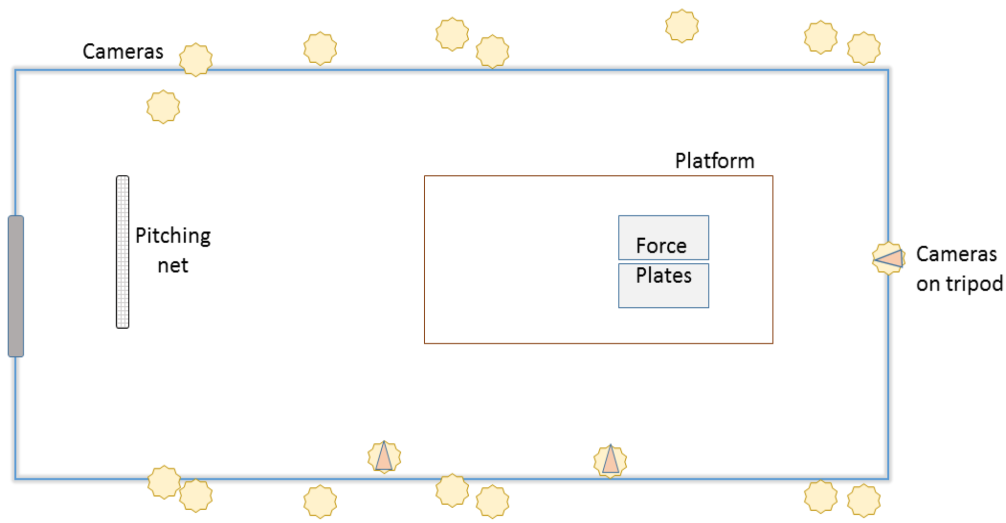
APPENDIX A

OMNI SCALE OF PERCEIVED EXERTION



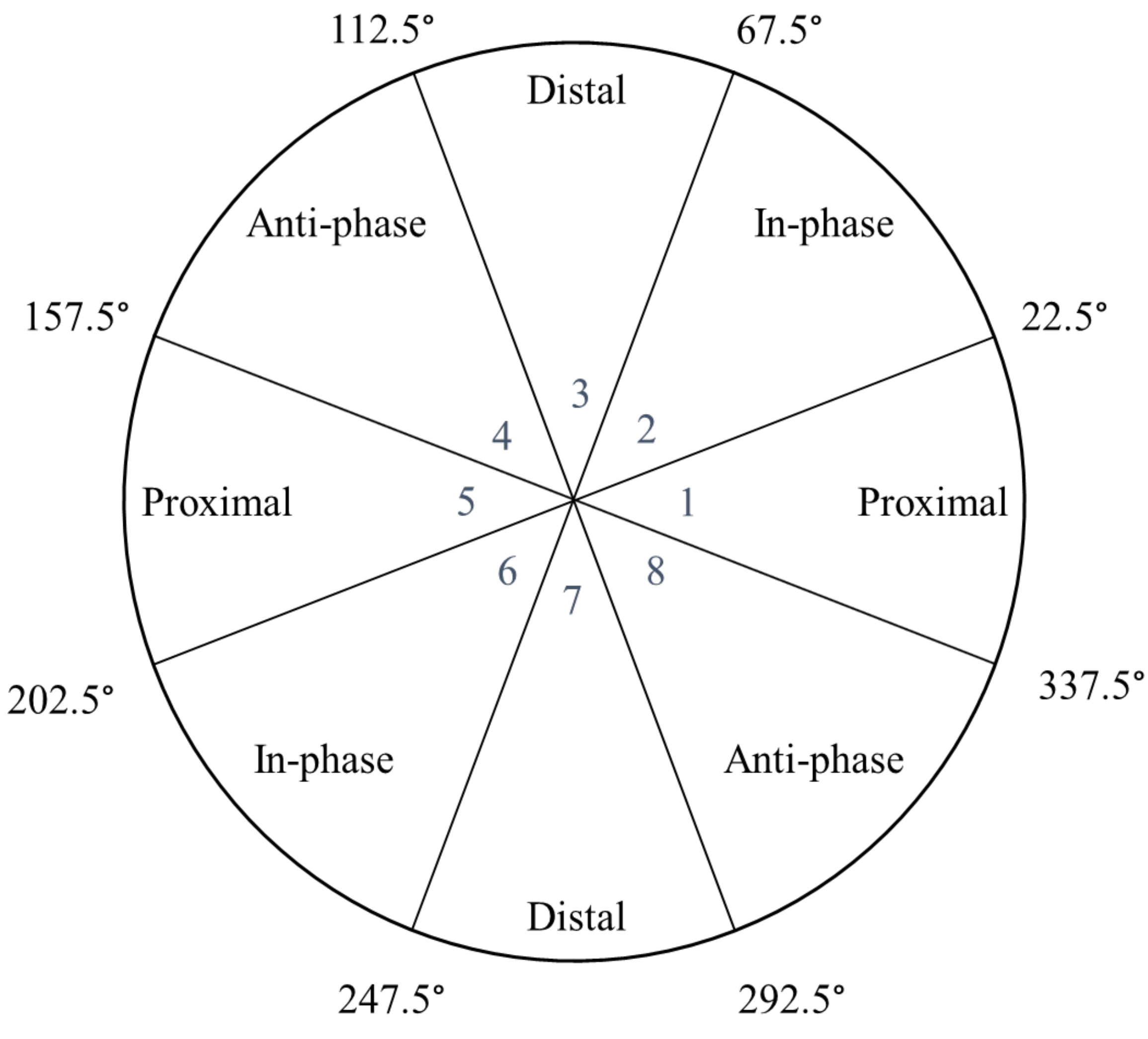
APPENDIX B

LABORATORY SET UP FOR SOFTBALL WINDMILL PITCHING



APPENDIX C

CLASSIFICATION OF COORDINATION PATTERN FROM THE COUPLING ANGLE

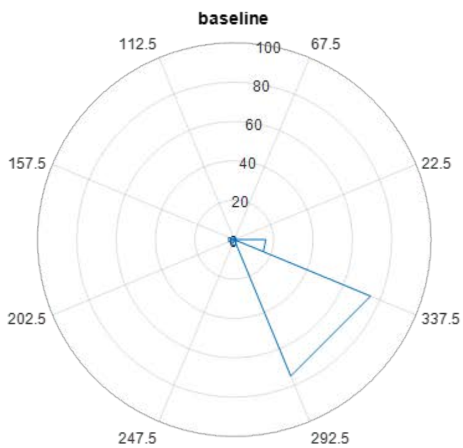


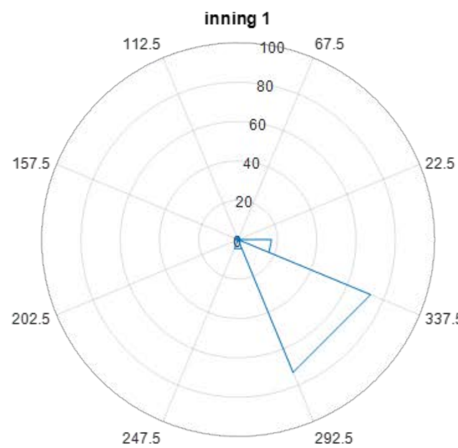
Bin number used in frequency count in center, couple angle degrees around perimeter of circle.

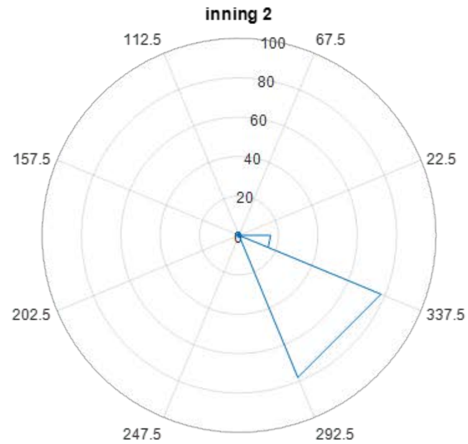
APPENDIX D

POLAR PLOTS OF SB04 AND SB10 FOR BASELINE AND ALL INNINGS

D.1 SB04 HUMERUS V FOREARM



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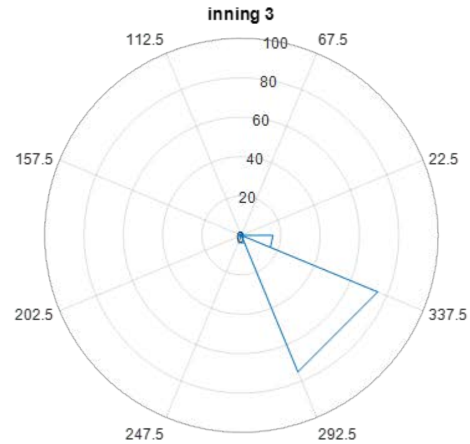
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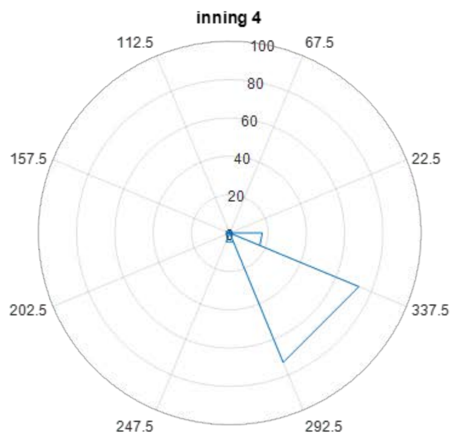
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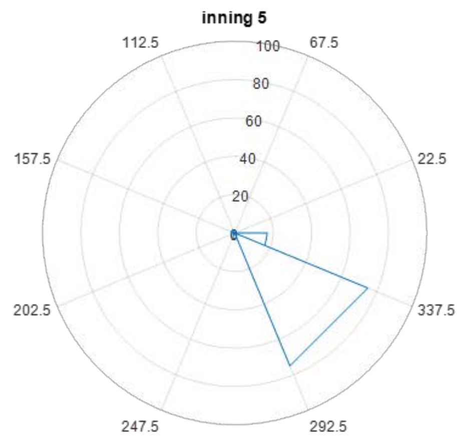
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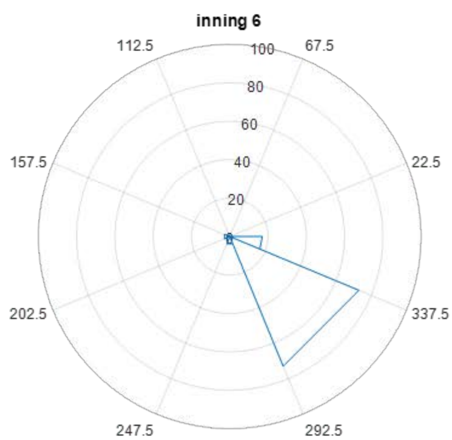
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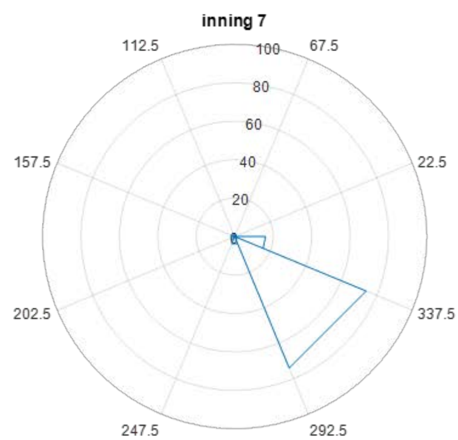
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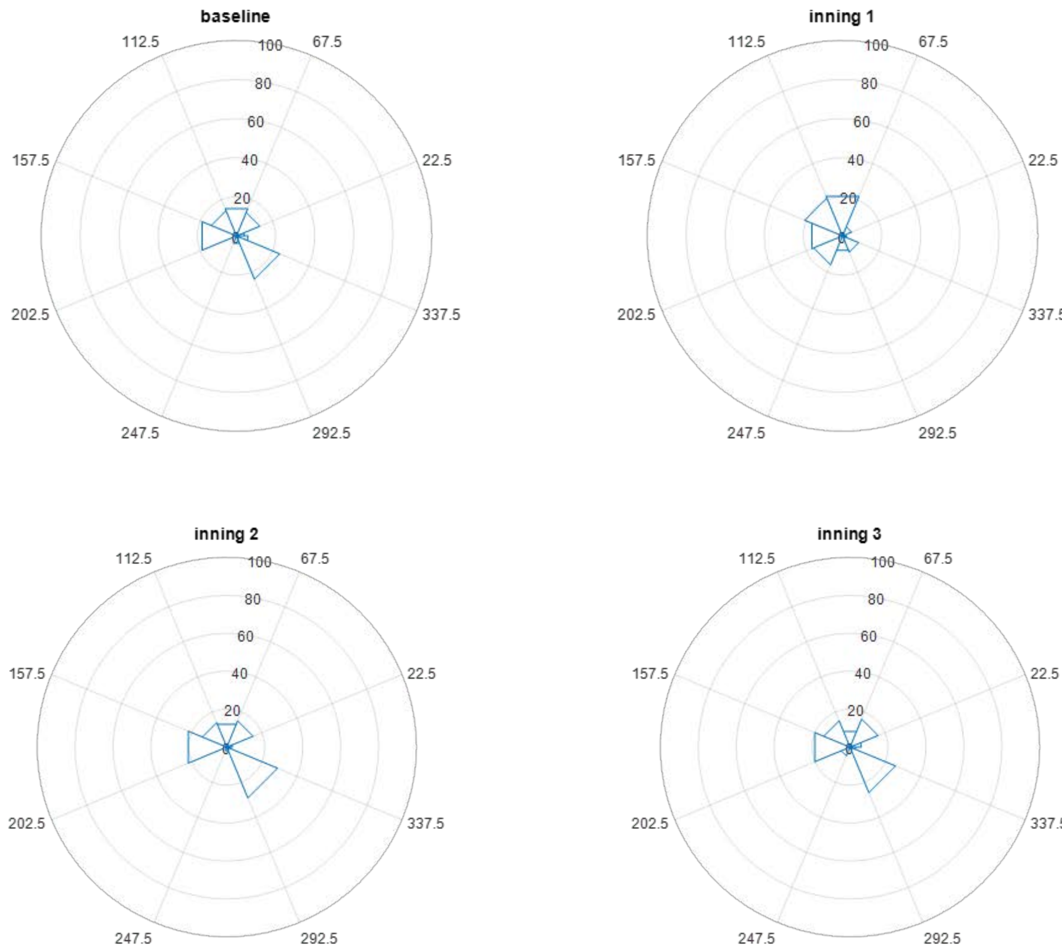

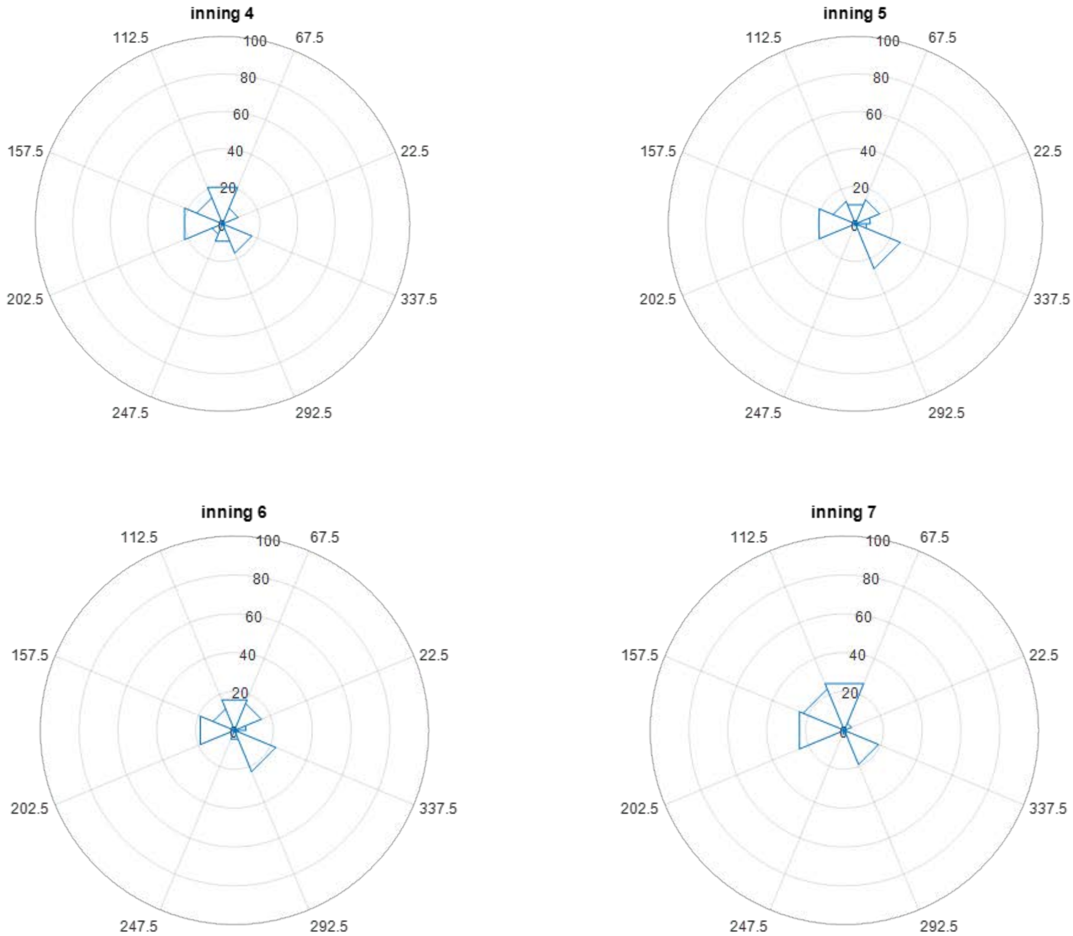

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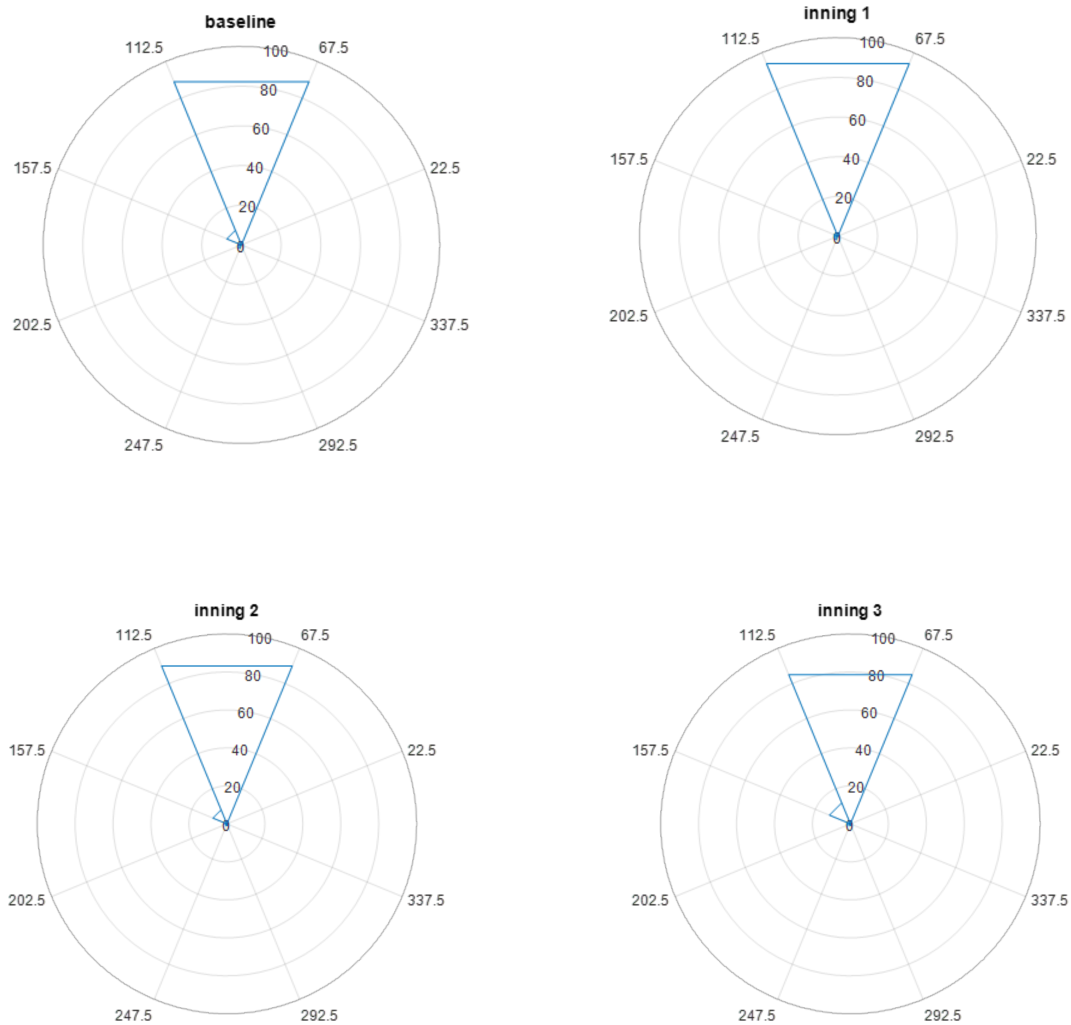

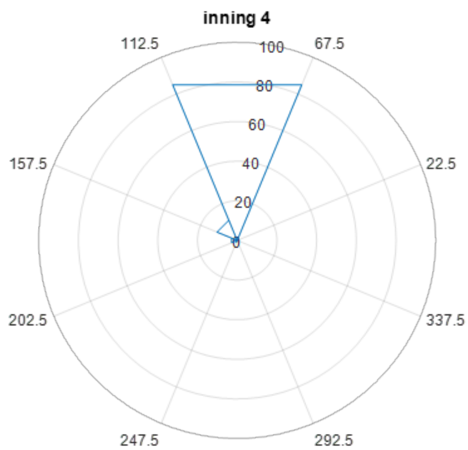
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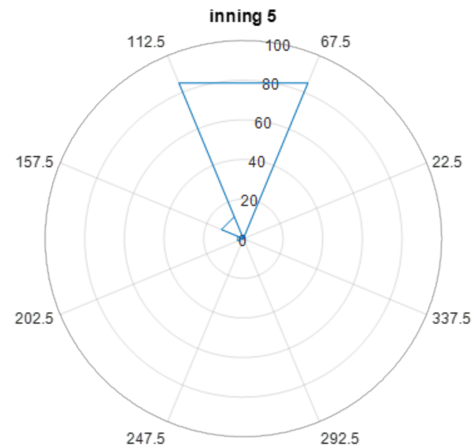
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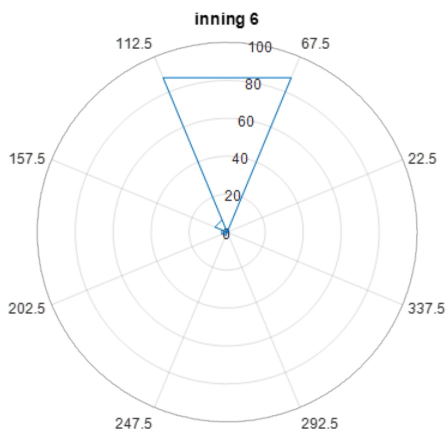
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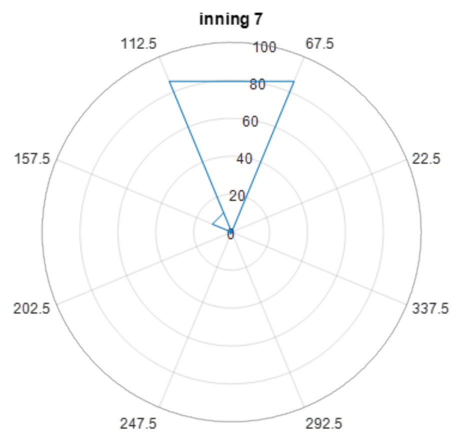
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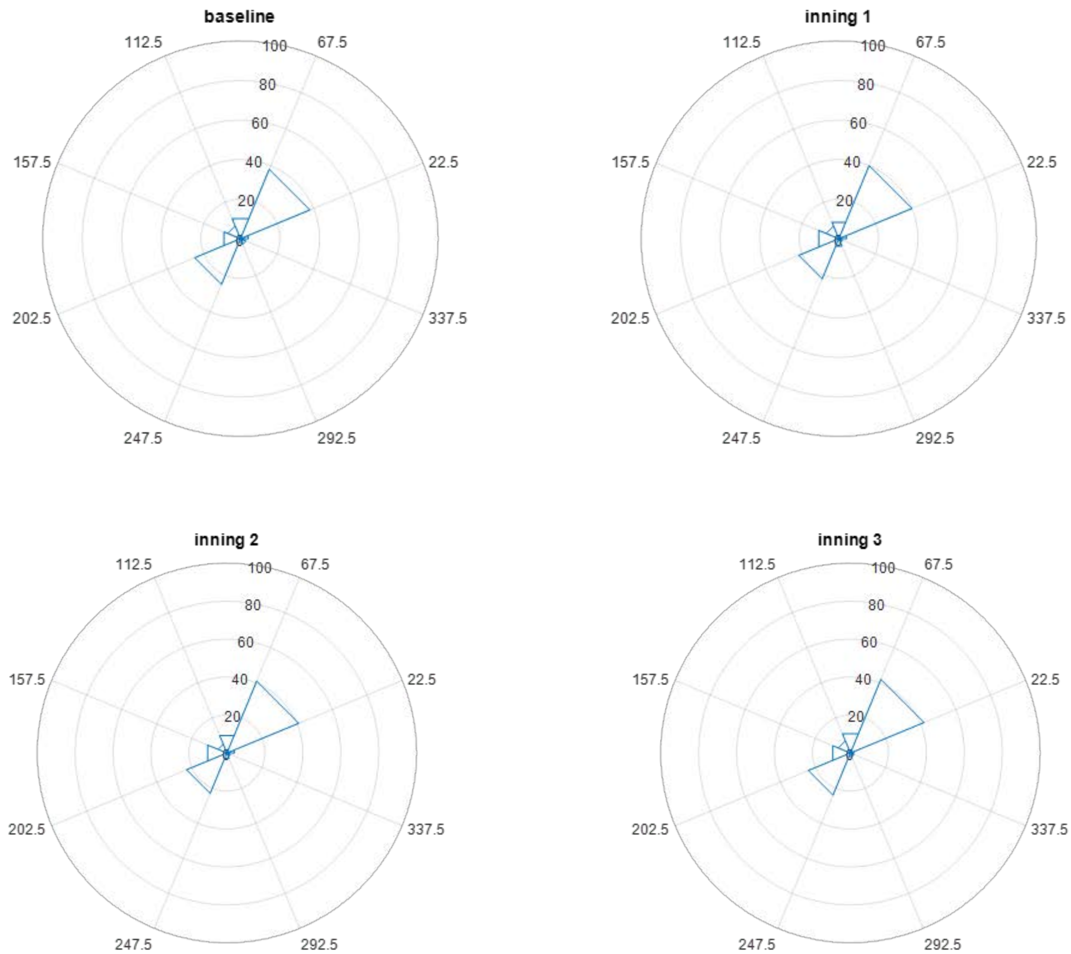
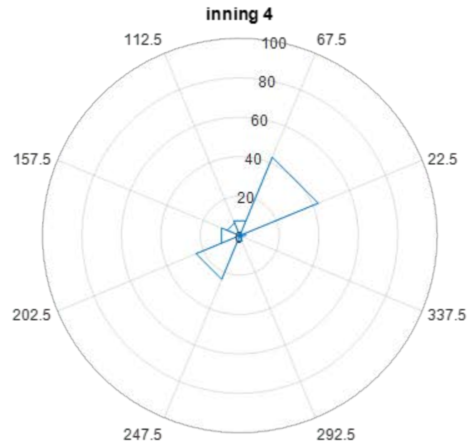
D.4 SB04 PELVIS V TORSO

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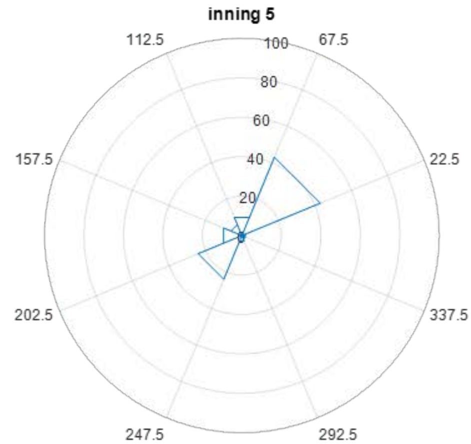
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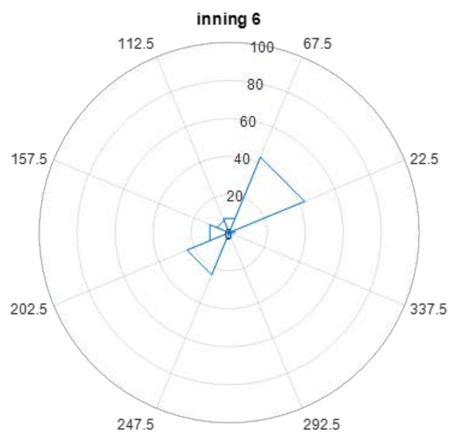
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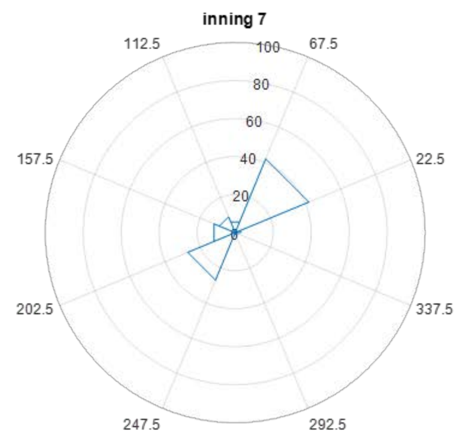
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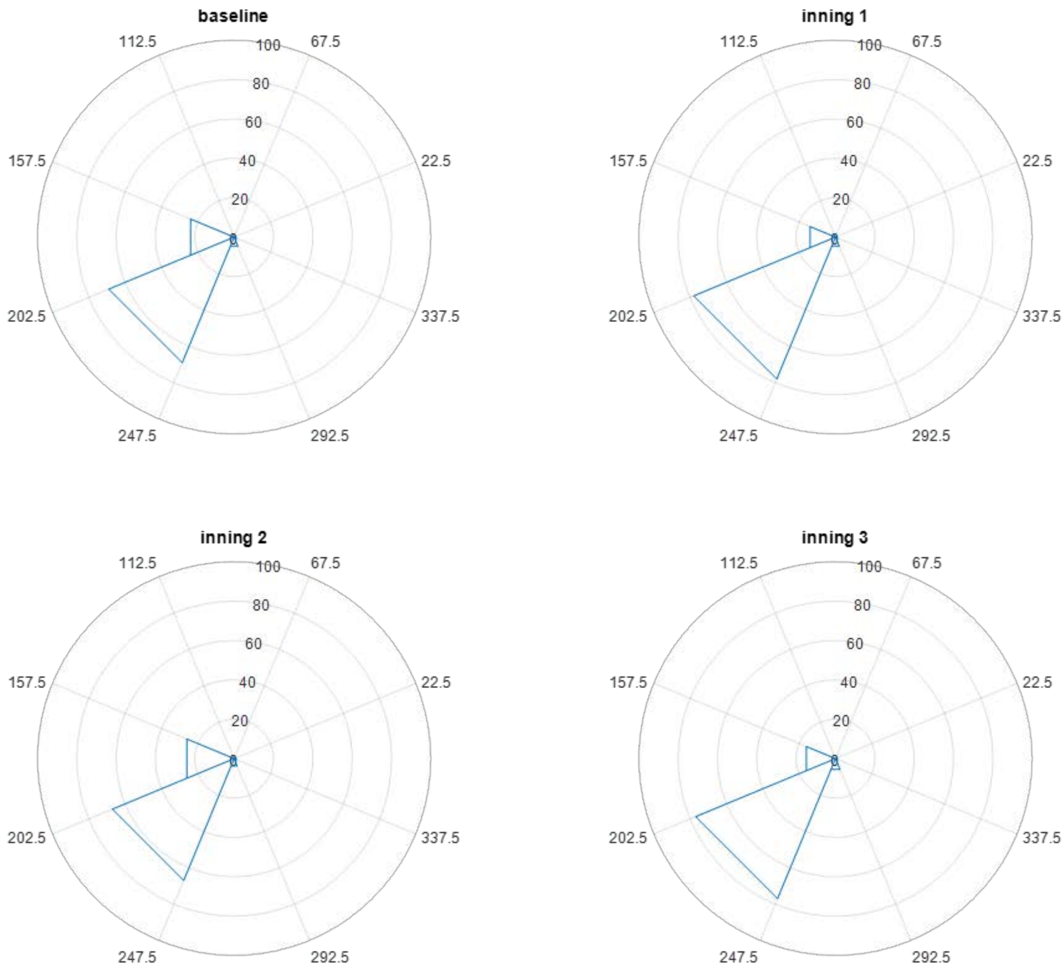

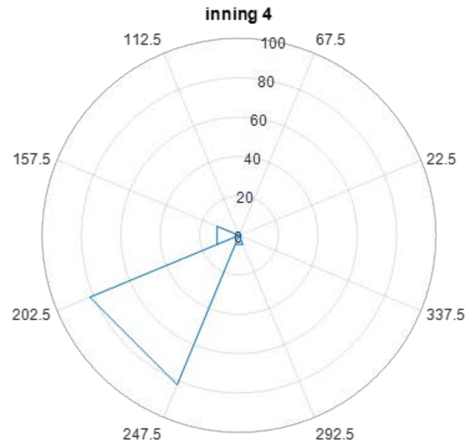
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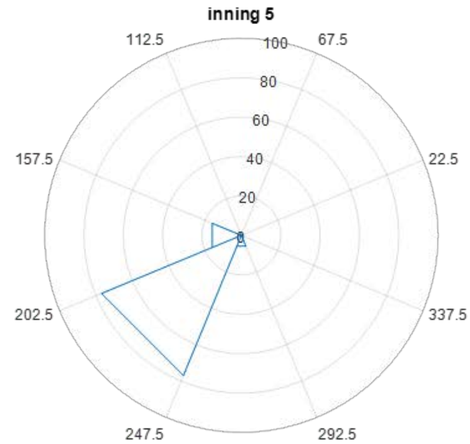
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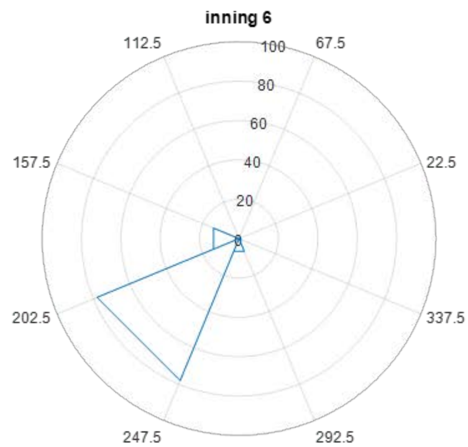
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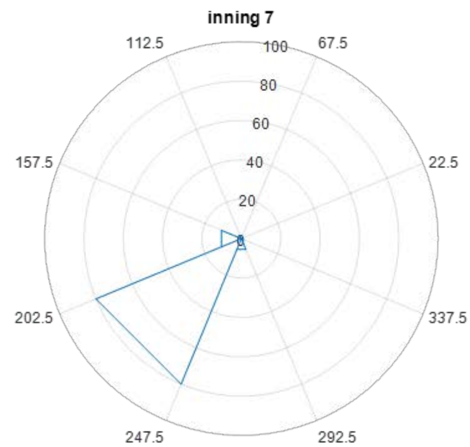
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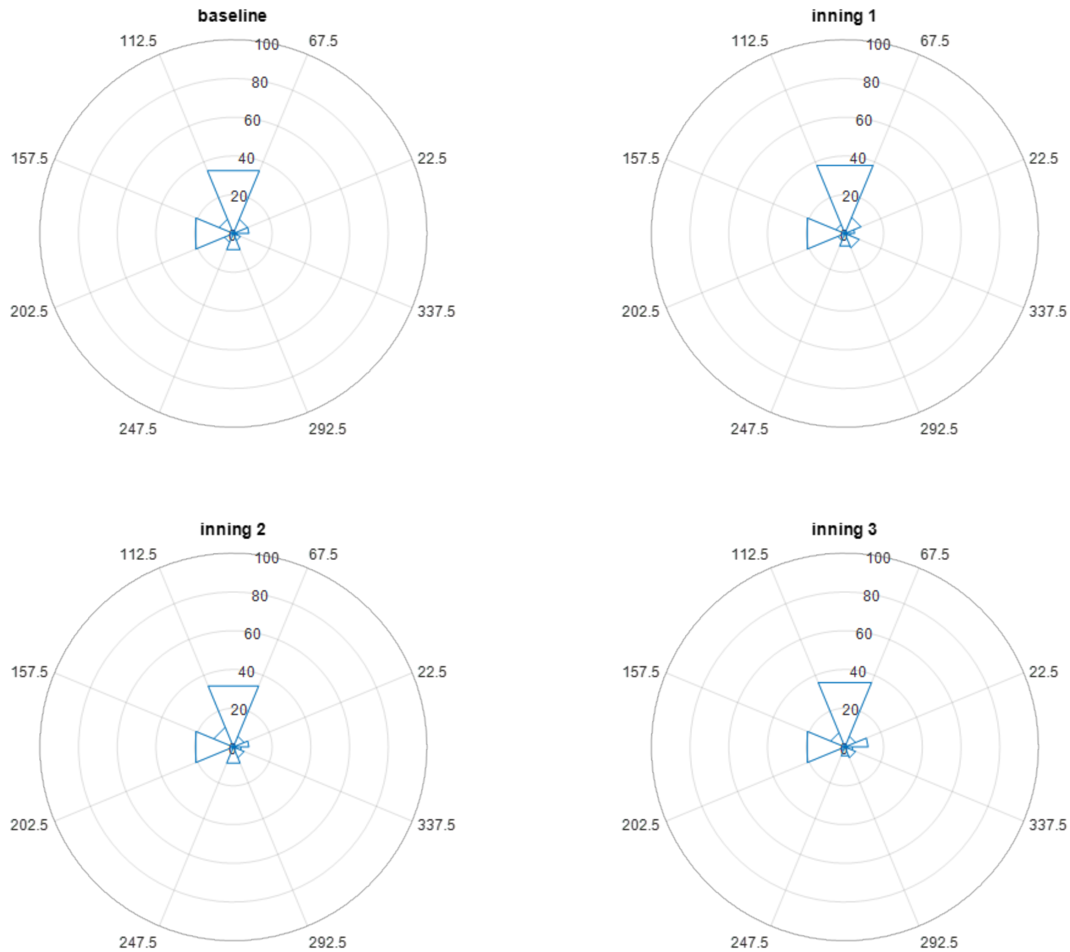
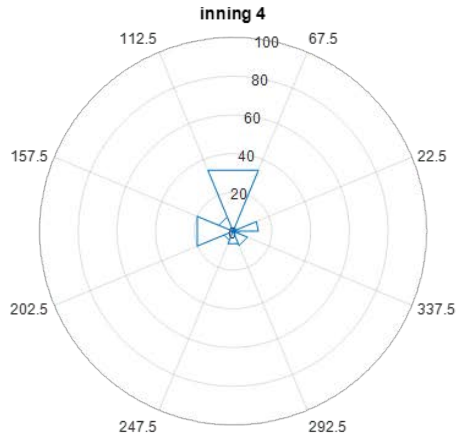
D.6 SB10 DRIVE LEG V PELVIS

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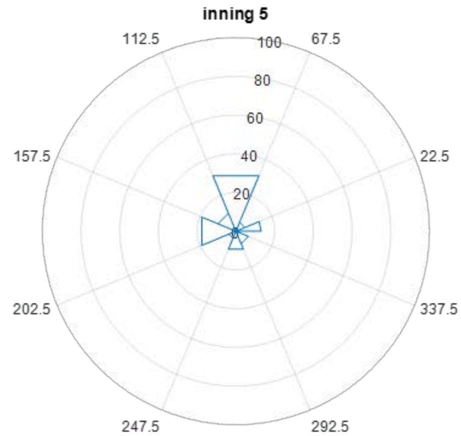
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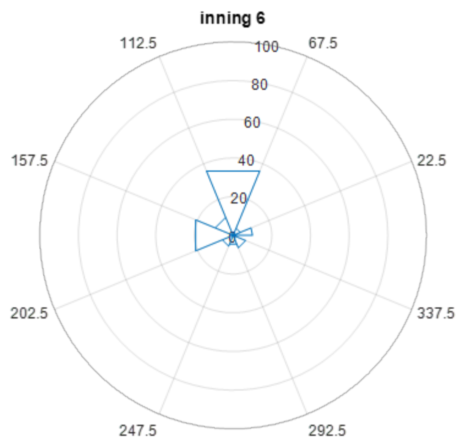
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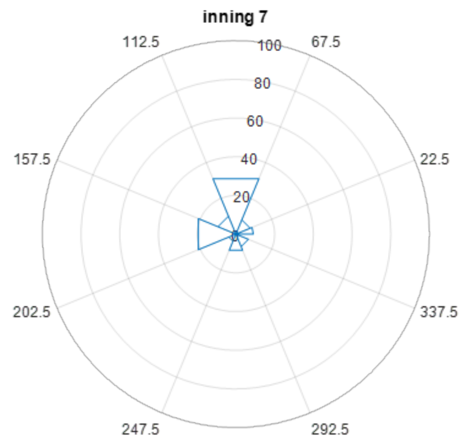
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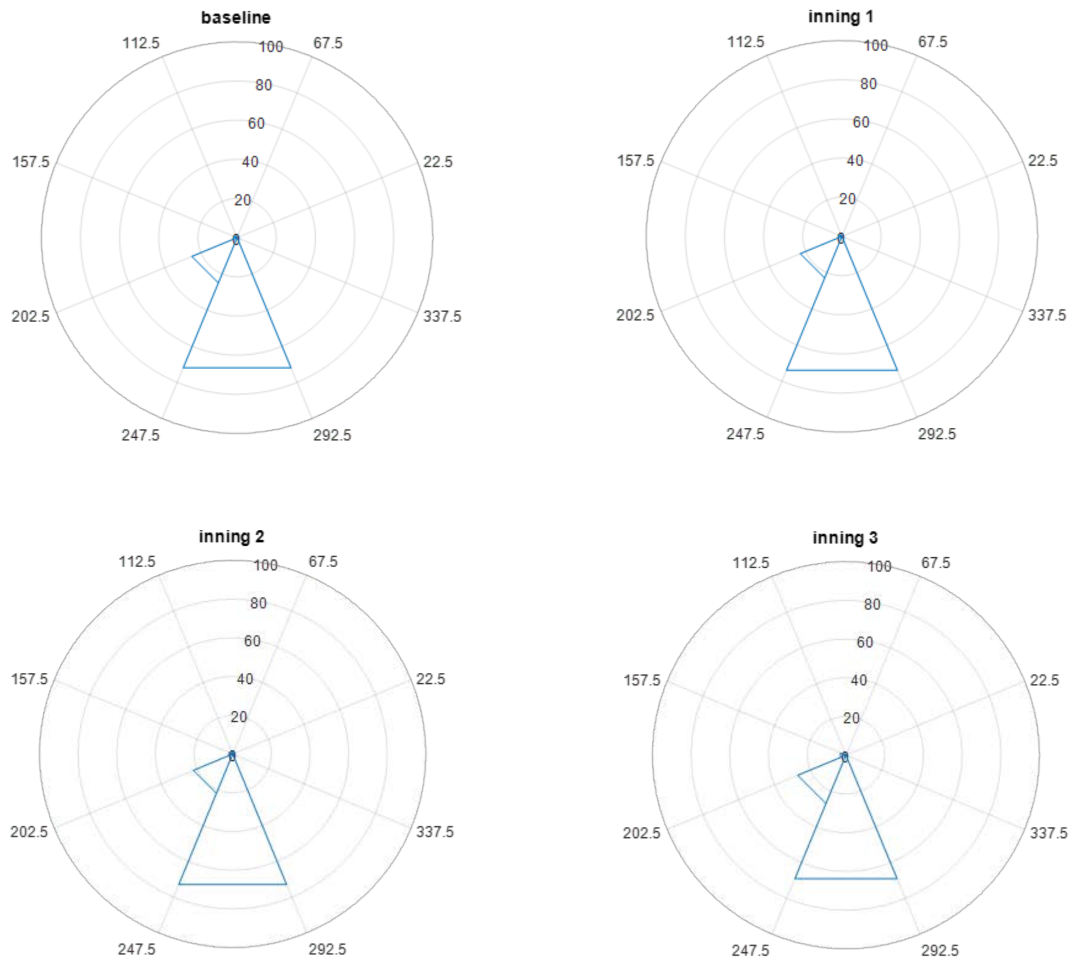
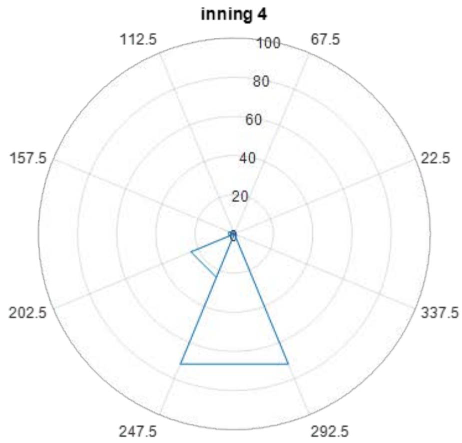
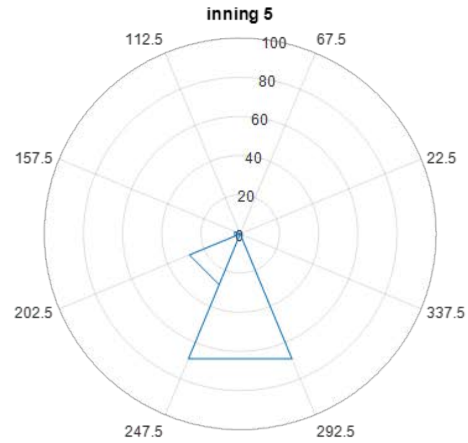
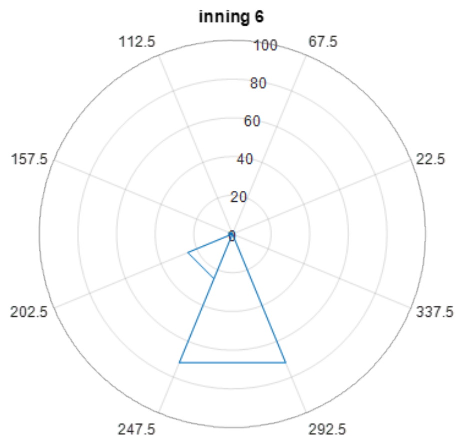
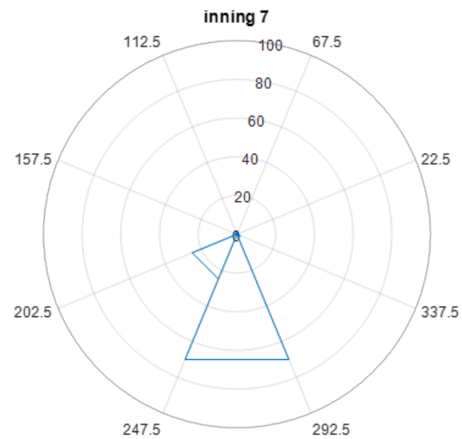
D.7 SB10 PELVIS V HUMERUS



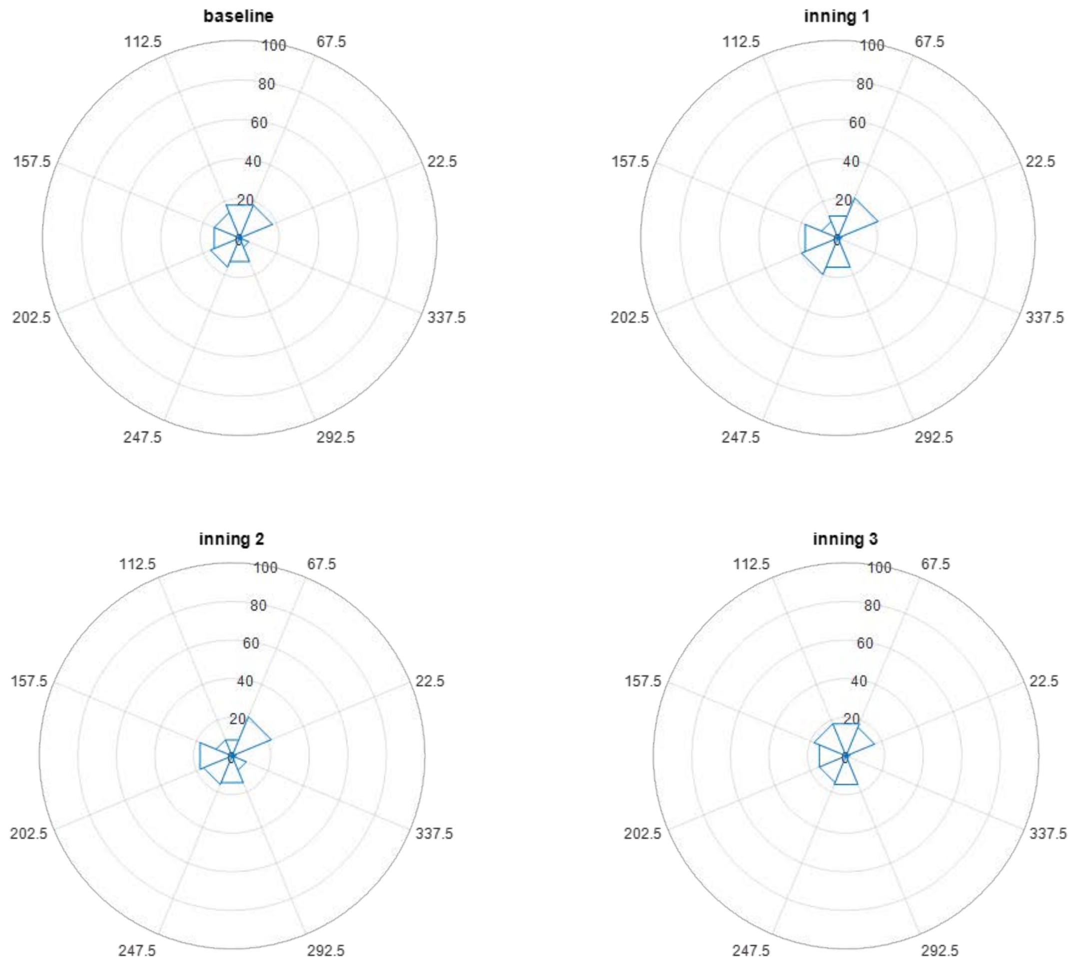

inning 4
112.5
100
67.5
80
60
157.5
40
22.5
20
0
202.5
337.5
247.5
292.5

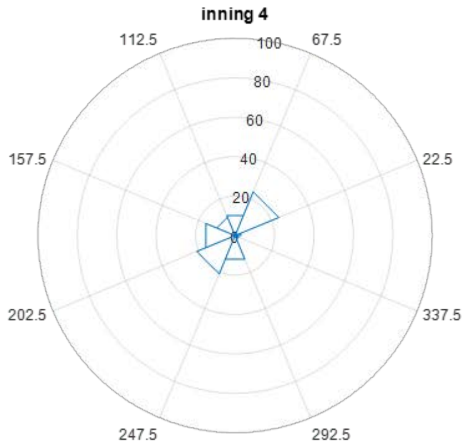

inning 5
112.5
100
67.5
80
60
157.5
40
22.5
20
0
202.5
337.5
247.5
292.5

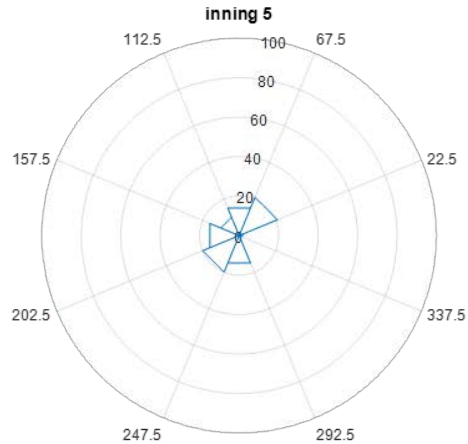

inning 6
112.5
100
67.5
80
60
157.5
40
22.5
20
0
202.5
337.5
247.5
292.5

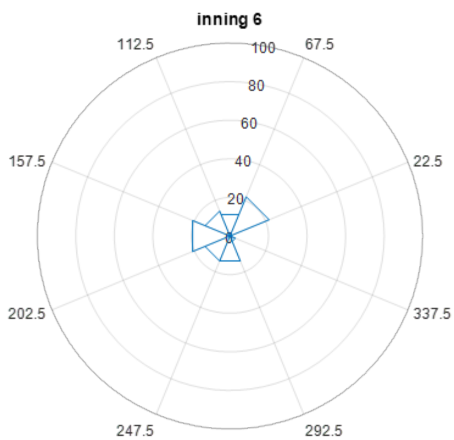

inning 7
112.5
100
67.5
80
60
157.5
40
22.5
20
0
202.5
337.5
247.5
292.5

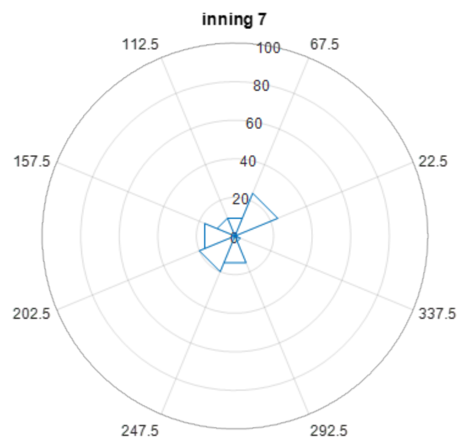
D.8 SB10 PELVIS V TORSO




inning 4
112.5
100
67.5
80
60
157.5
40
22.5
20
202.5
337.5
247.5
292.5


inning 5
112.5
100
67.5
80
60
157.5
40
22.5
20
202.5
337.5
247.5
292.5

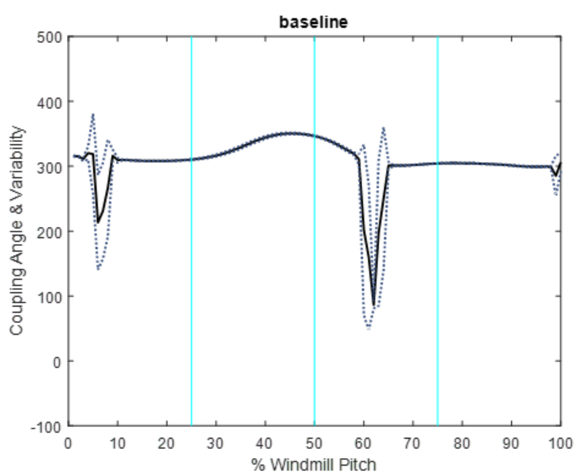

inning 6
112.5
100
67.5
80
60
157.5
40
22.5
20
202.5
337.5
247.5
292.5

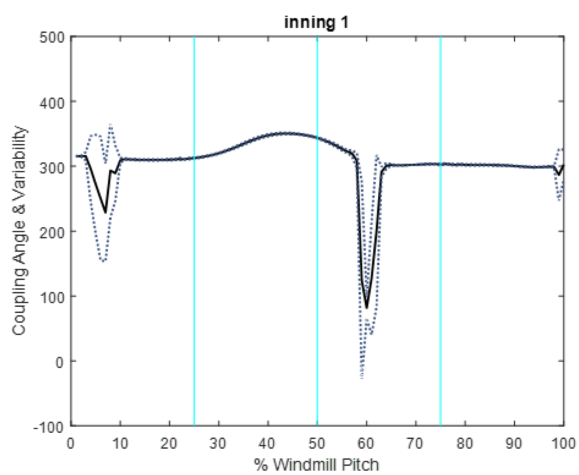

inning 7
112.5
100
67.5
80
60
157.5
40
22.5
20
202.5
337.5
247.5
292.5

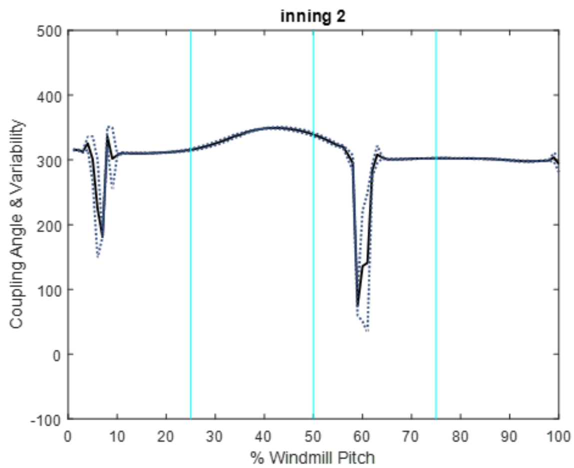
APPENDIX E

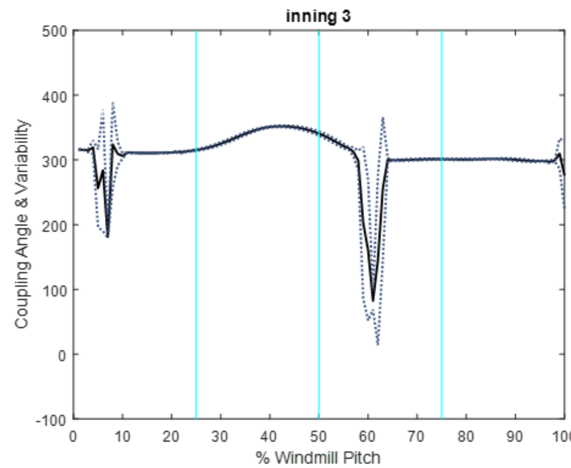
AVERAGE COUPLING ANGLE AND COUPLING ANGLE VARIABILITY OF SB04 AND SB10 FOR BASELINE AND ALL INNINGS

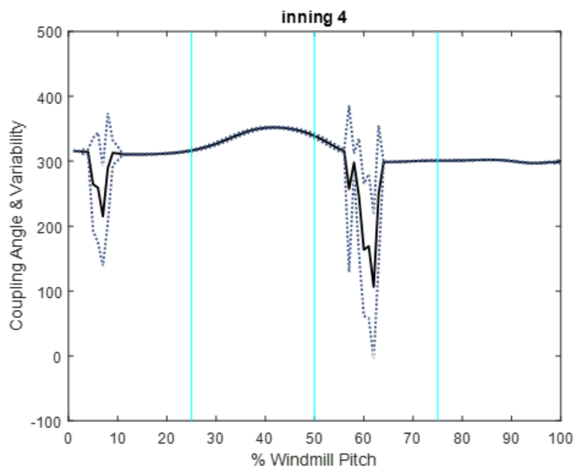
E.1 SB04 HUMERUS V FOREARM

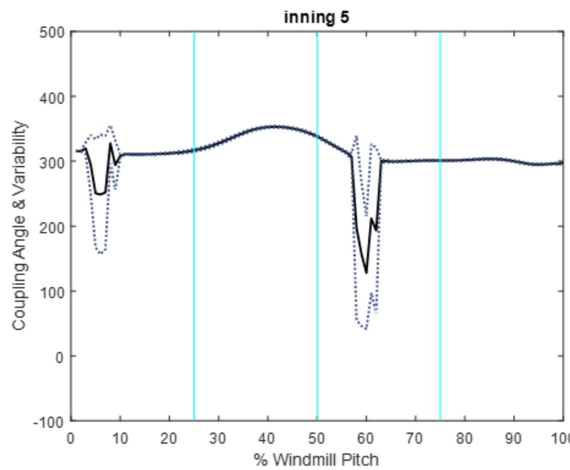


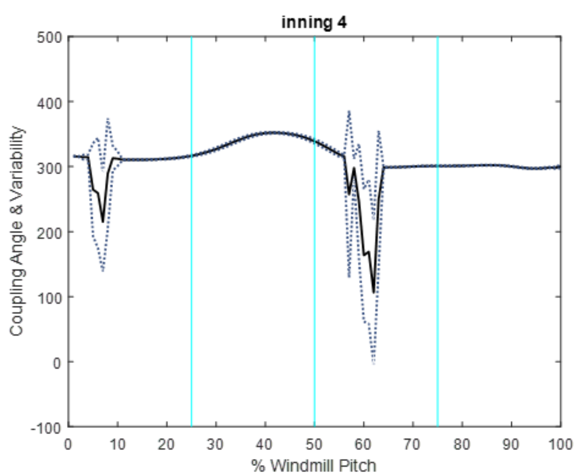


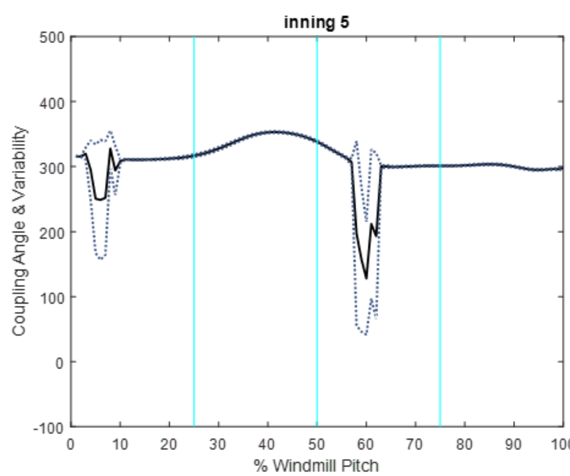

inning 2
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

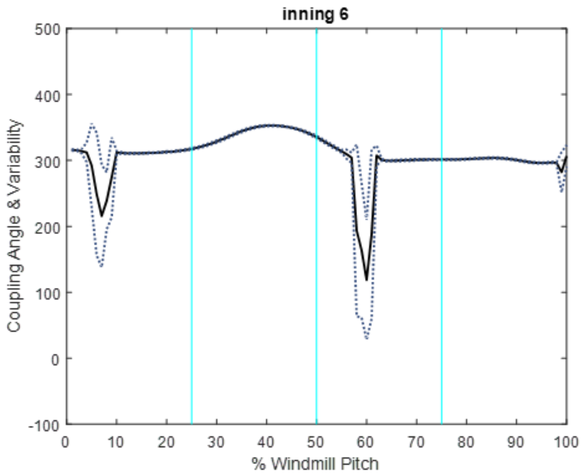

inning 3
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

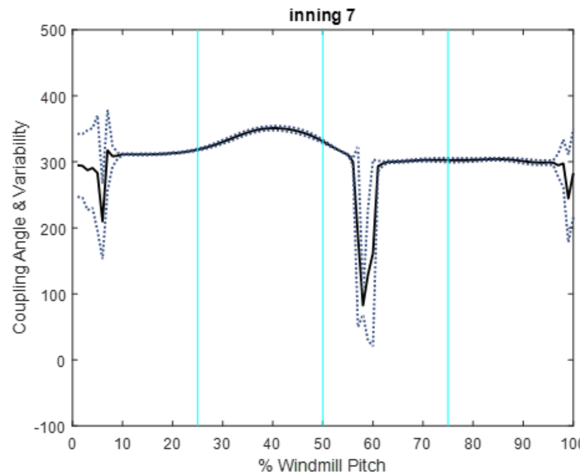

inning 4
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100


inning 5
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

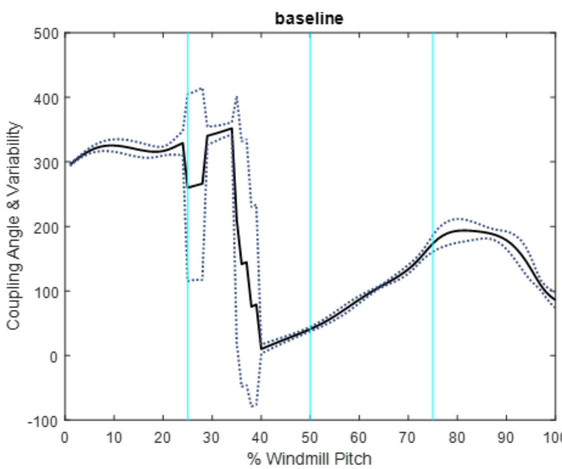

inning 4
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

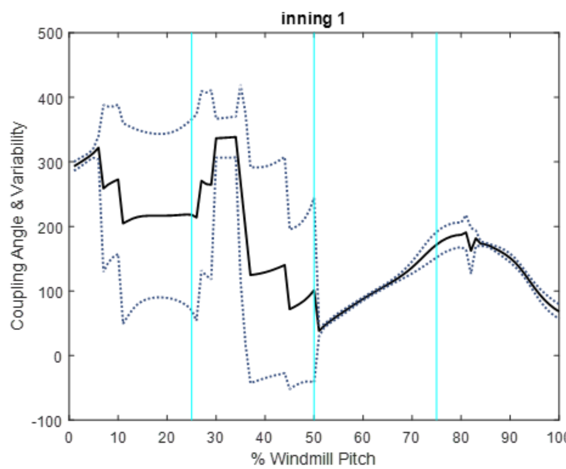

inning 5
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

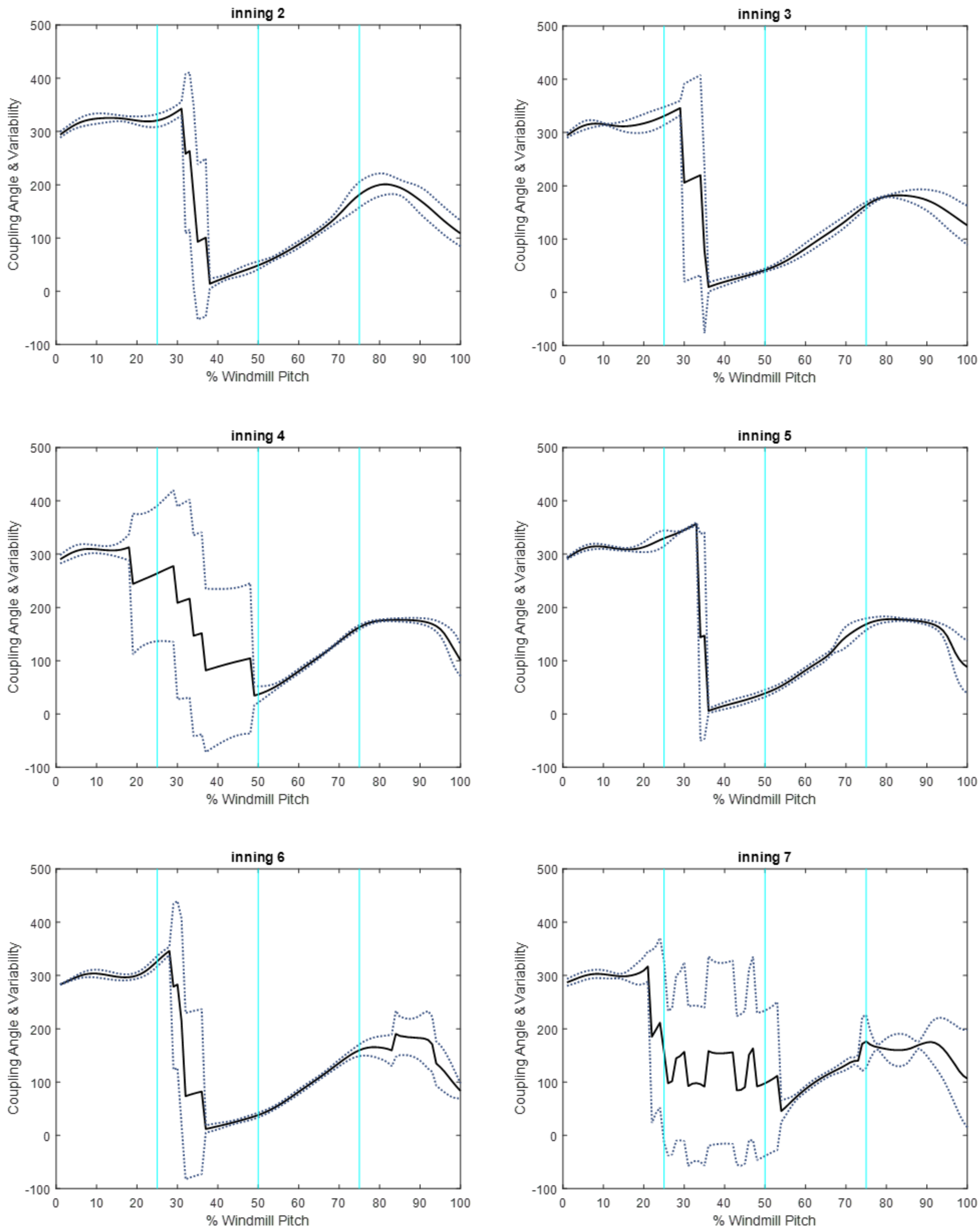




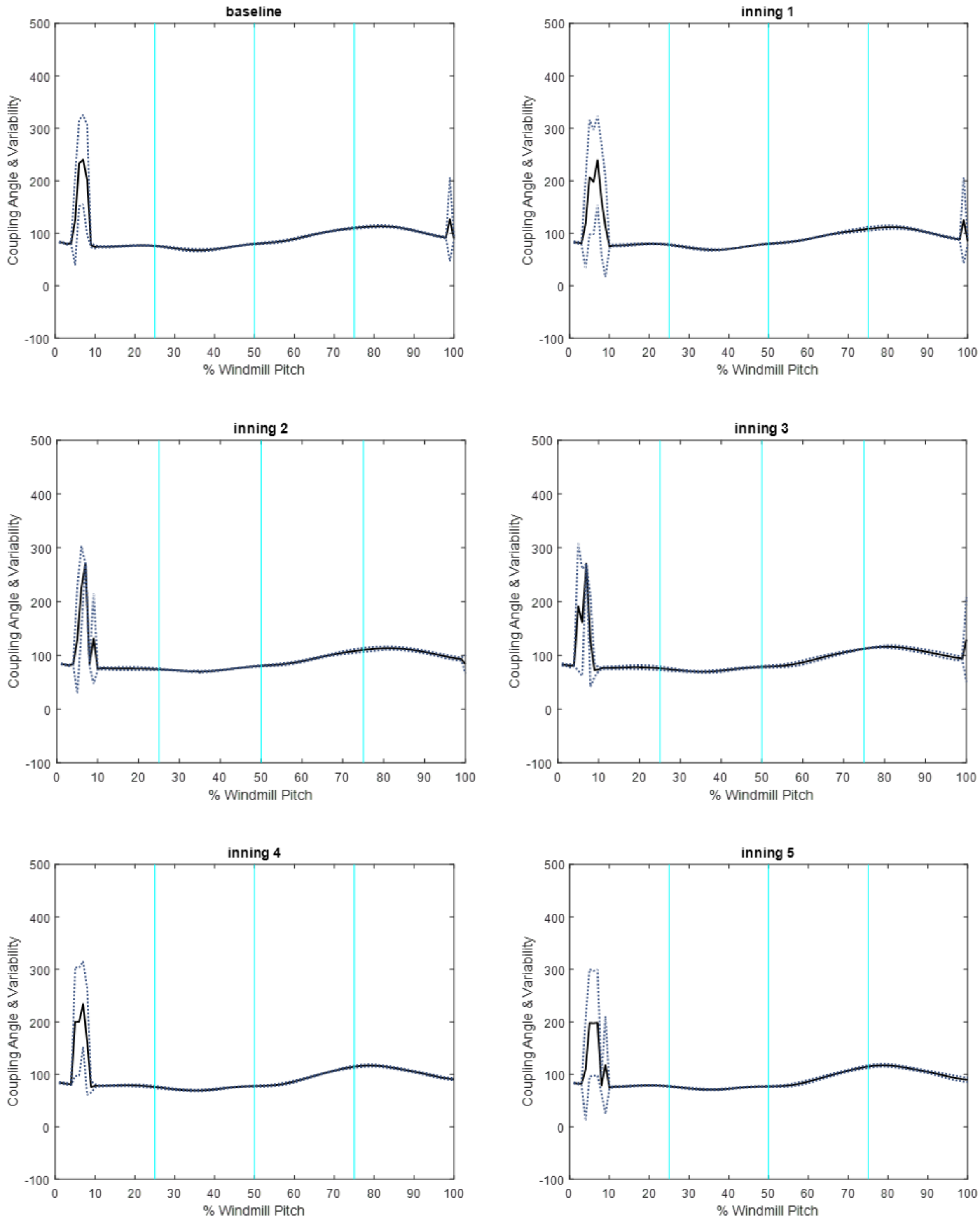
E.2 SB04 DRIVE LEG V PELVIS

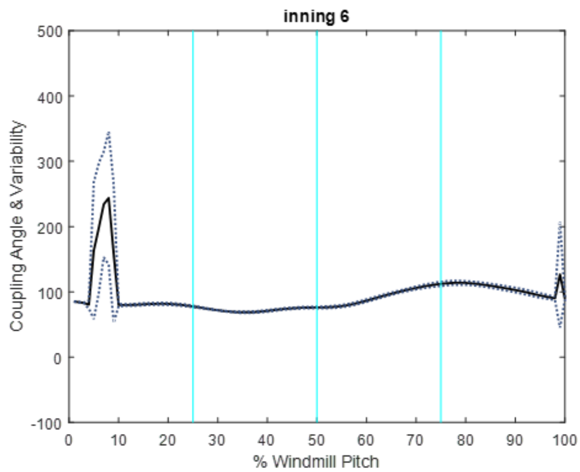


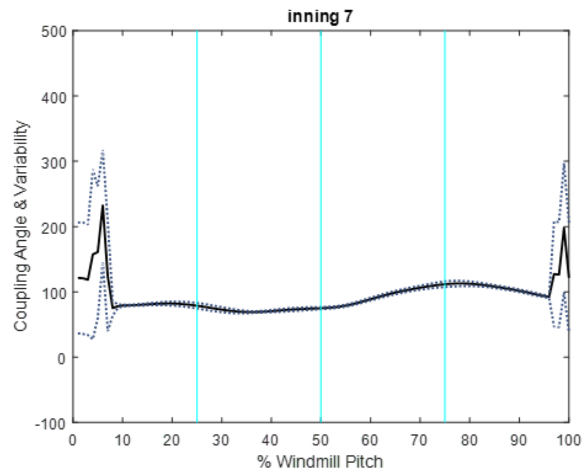



inning 2
inning 3
inning 4
inning 5
inning 6
inning 7
Coupling Angle & Variability
% Windmill Pitch

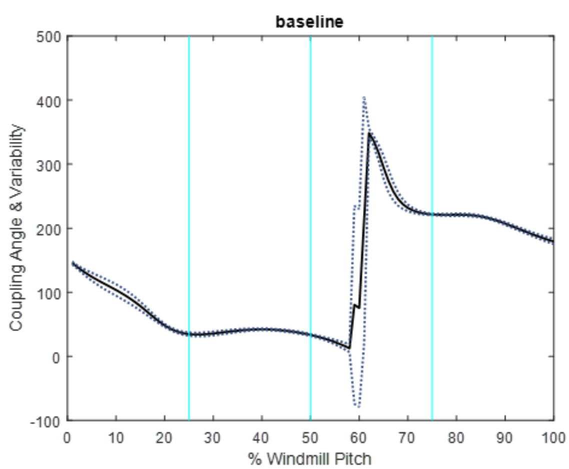
E.3 SB04 PELVIS V HUMERUS

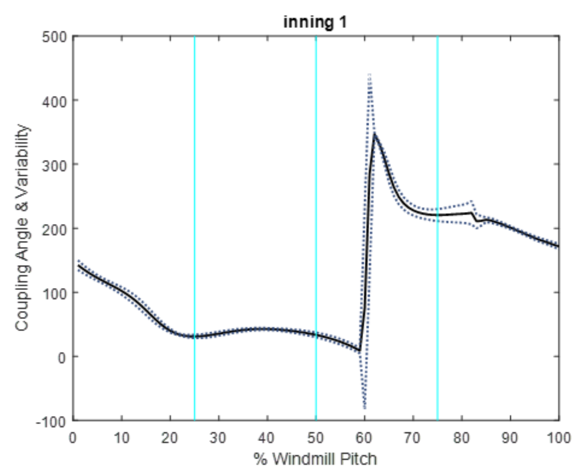


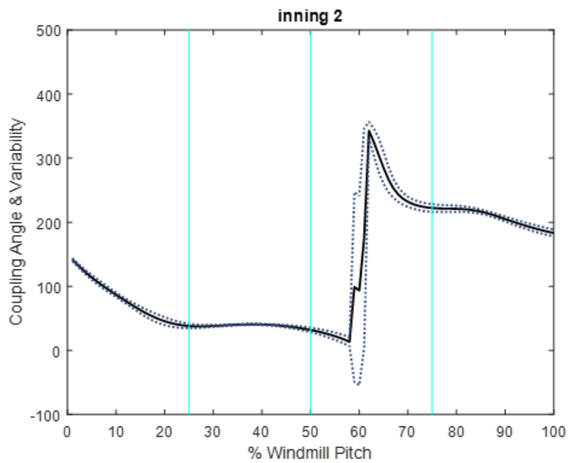


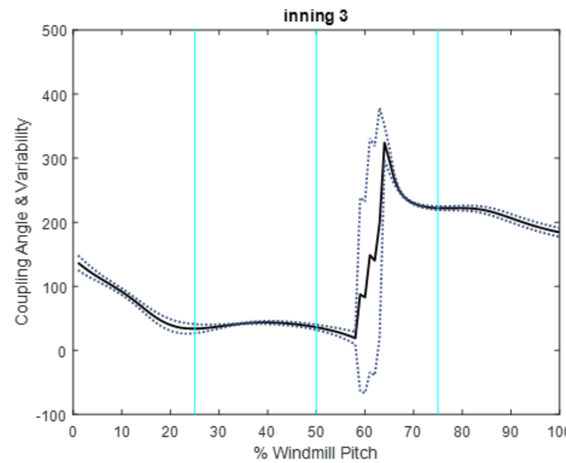


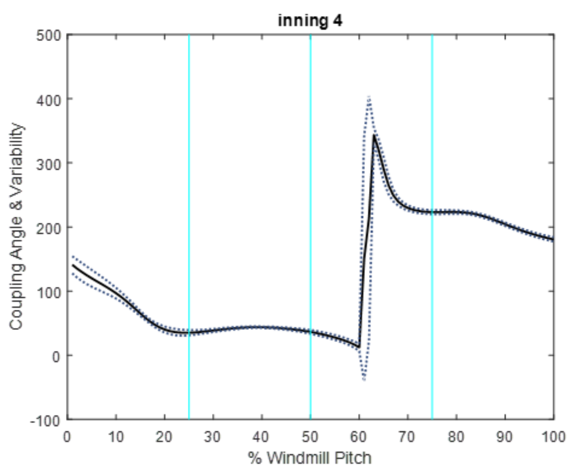
E.4 SB04 PELVIS V TORSO

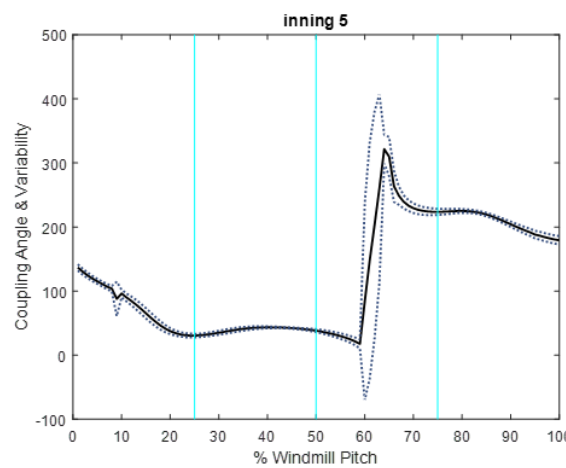


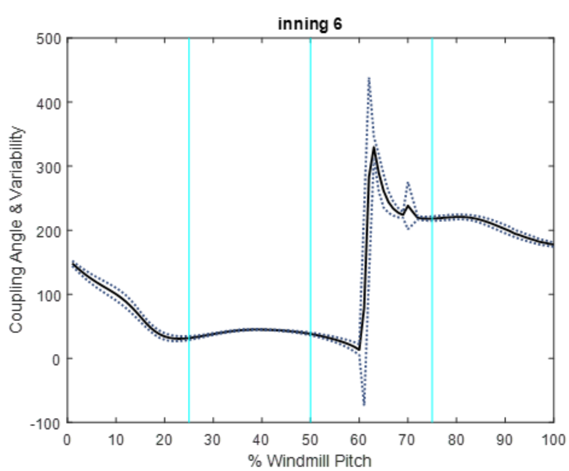


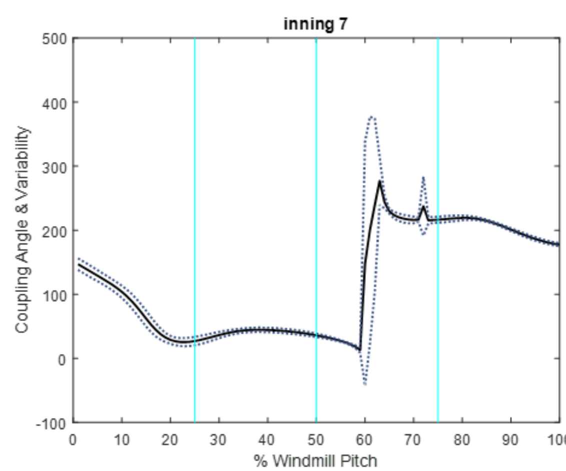

inning 2
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100


inning 3
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

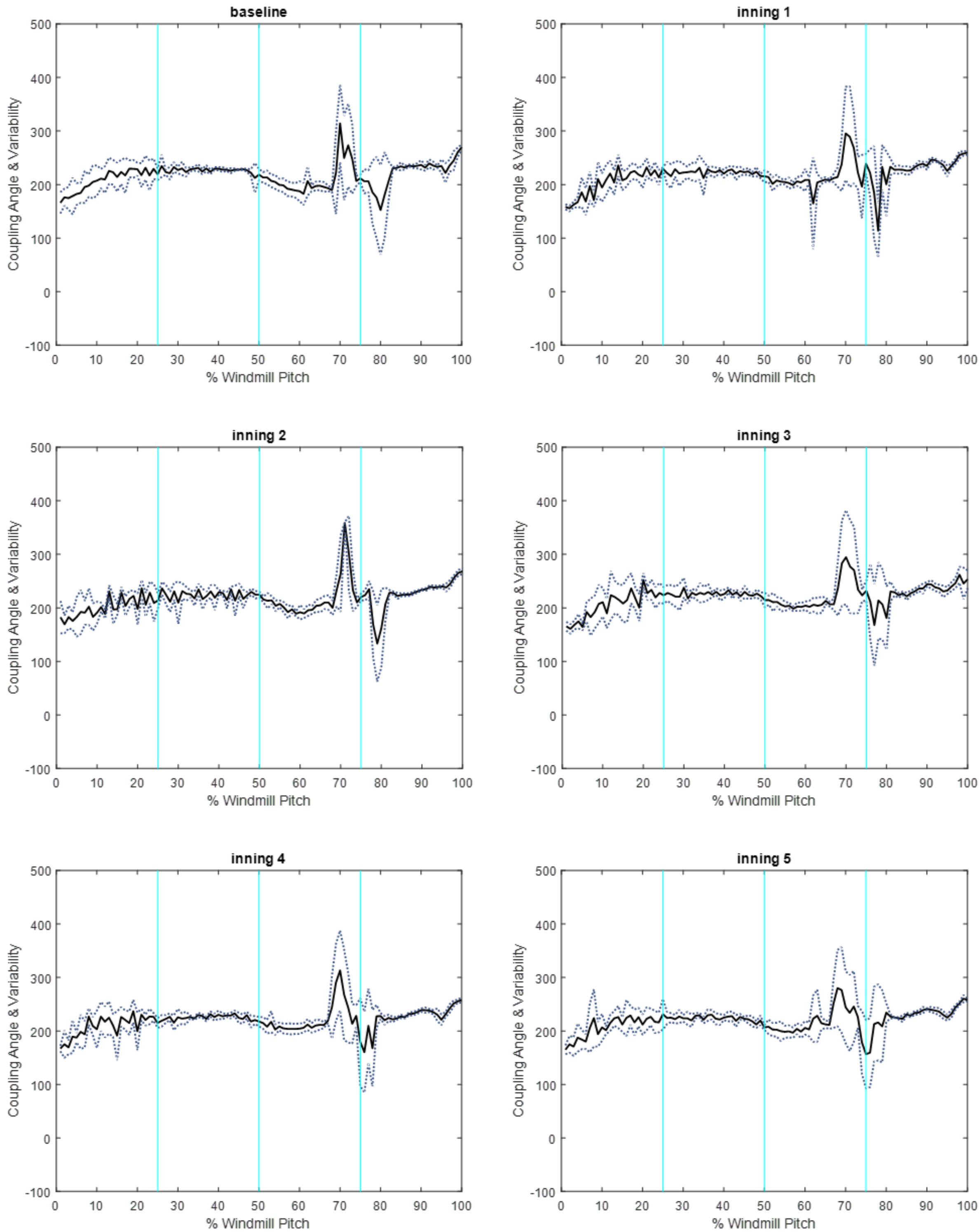

inning 4
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

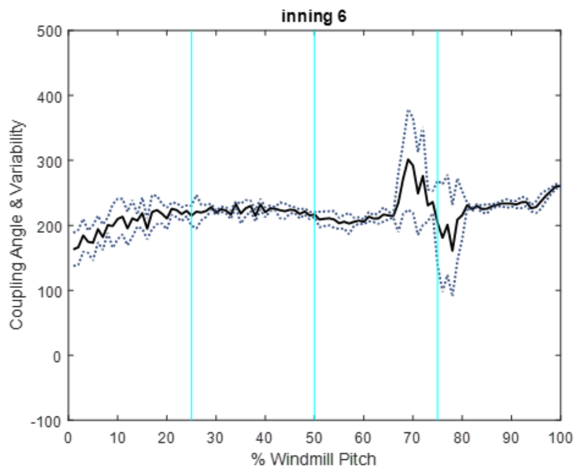

inning 5
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

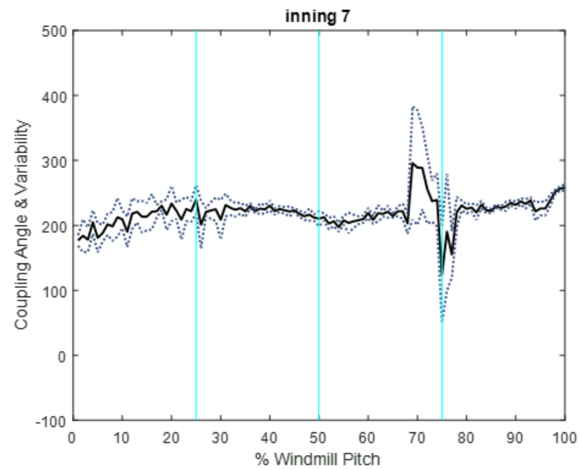

inning 6
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100


inning 7
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

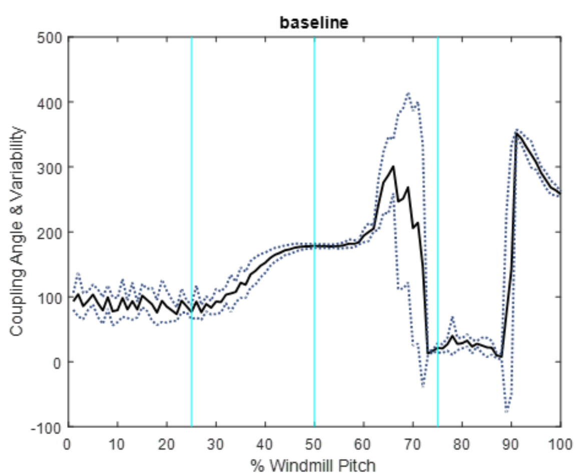
E.5 SB10 HUMERUS V FOREARM

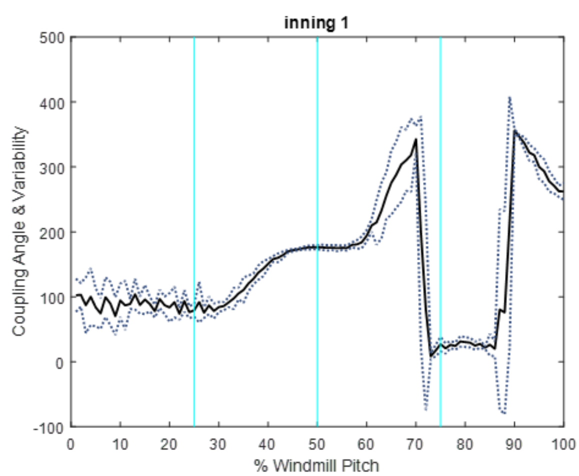


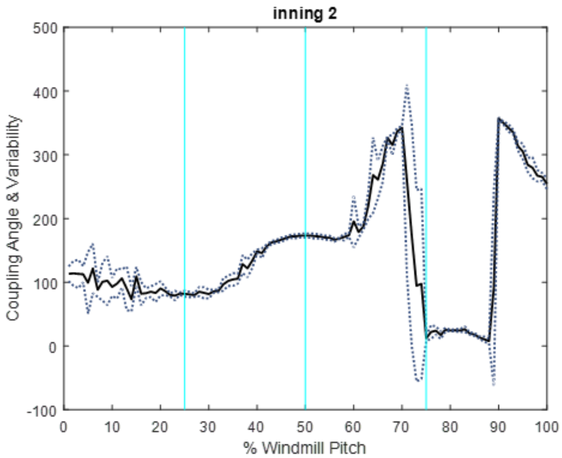


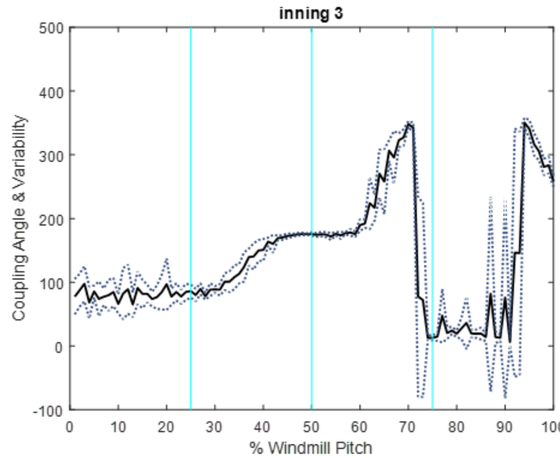


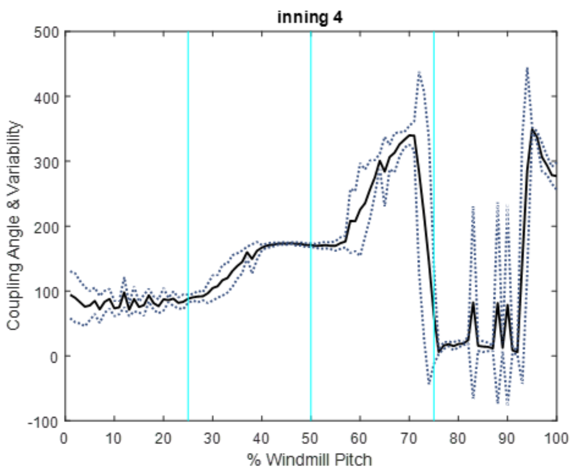
E.6 SB10 DRIVE LEG V PELVIS

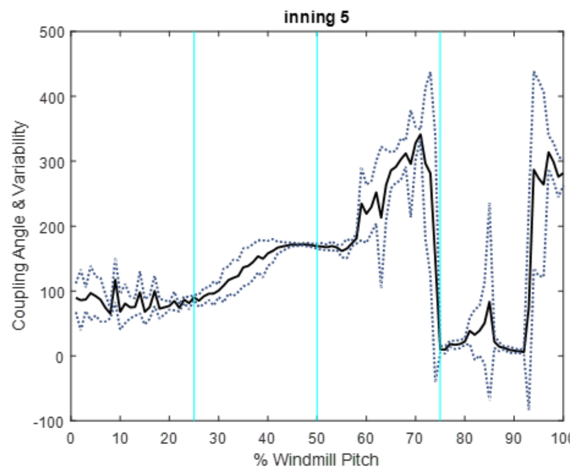


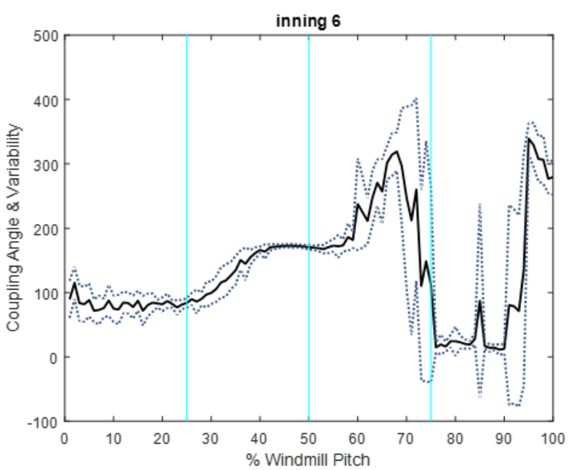


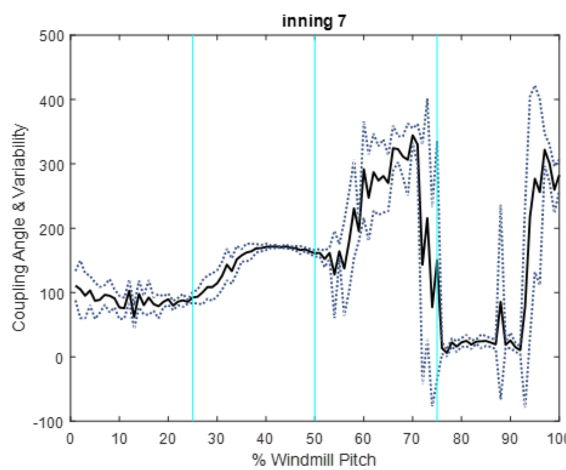

inning 2
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100


inning 3
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

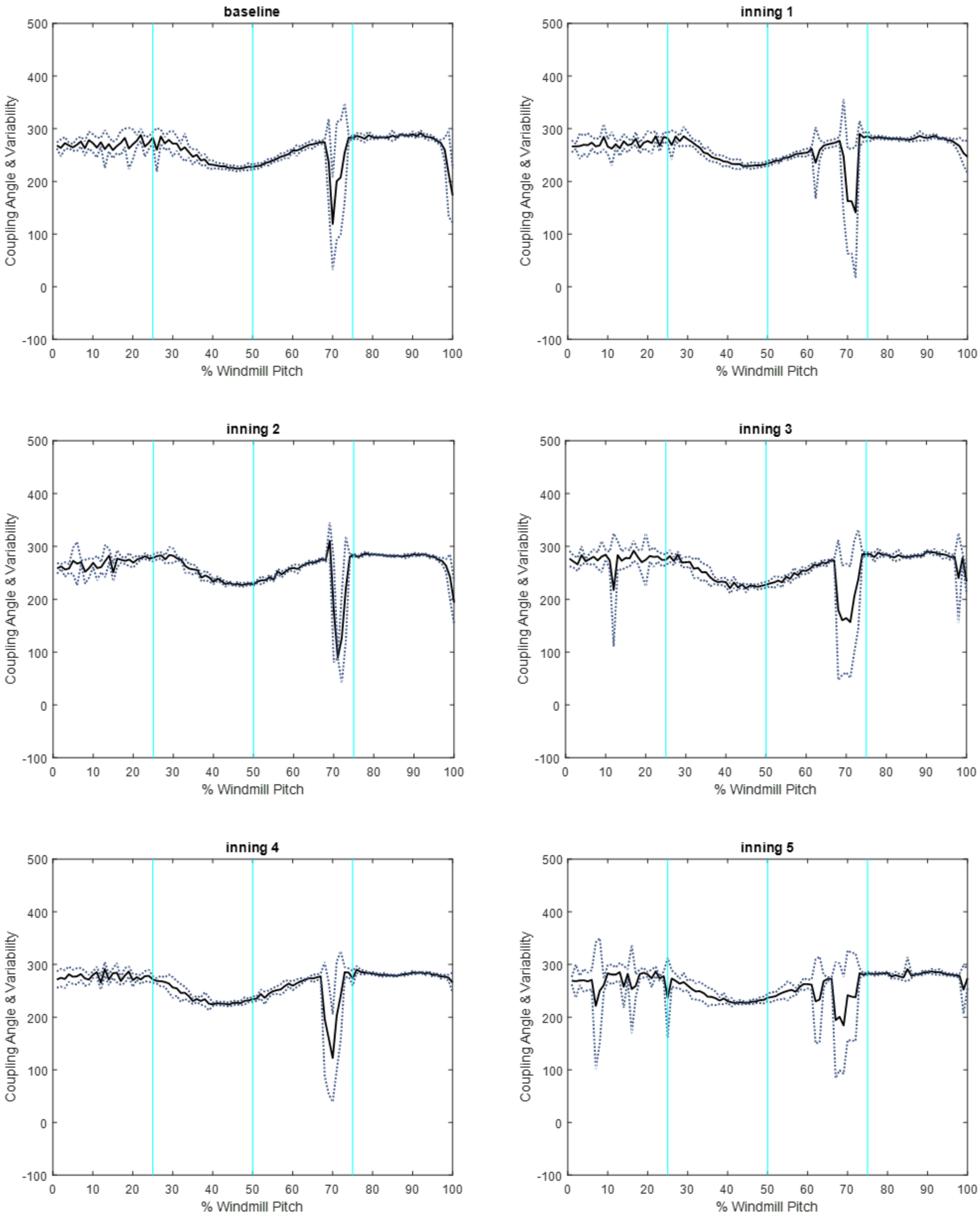

inning 4
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

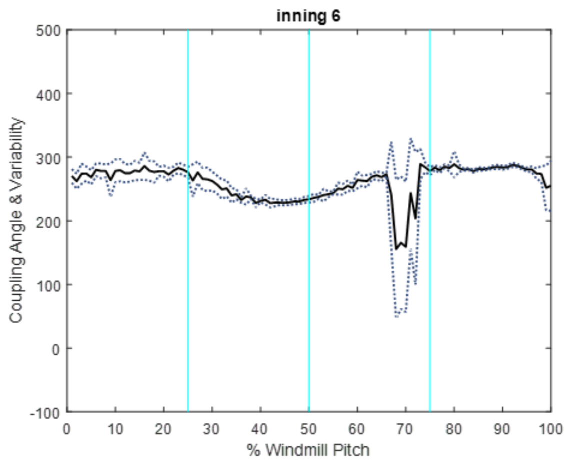

inning 5
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

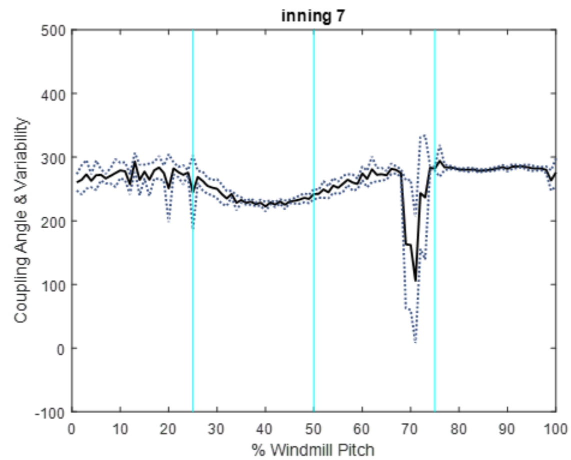

inning 6
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100


inning 7
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

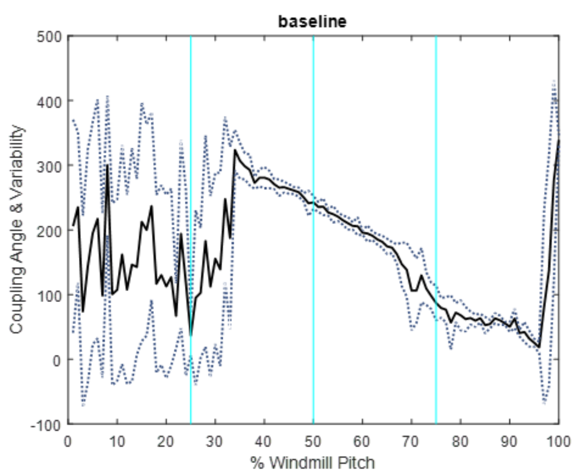
E.7 SB10 PELVIS V HUMERUS

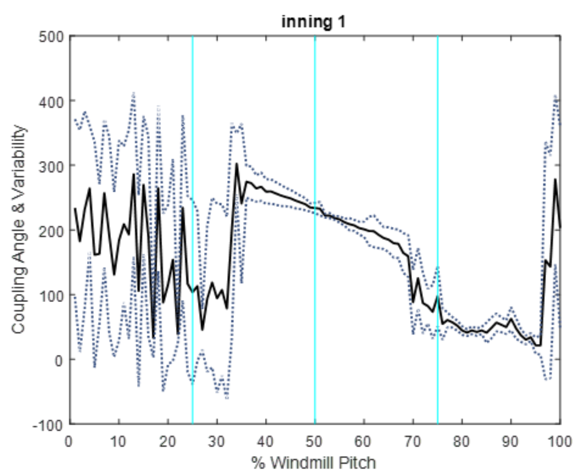


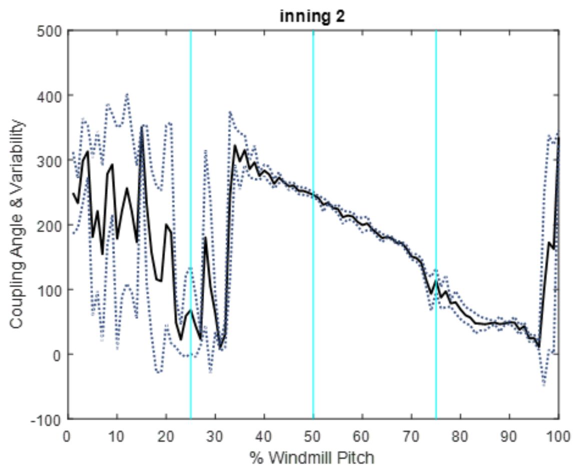


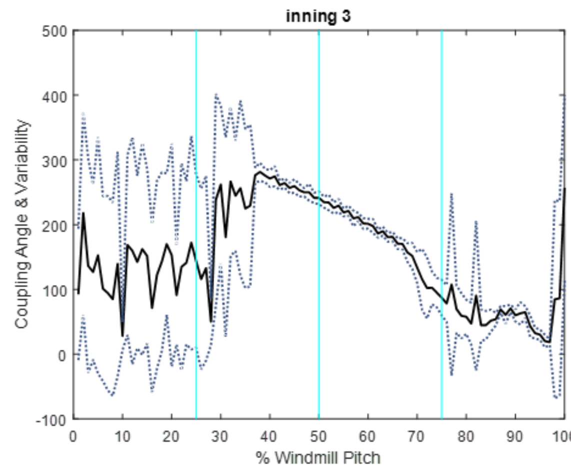


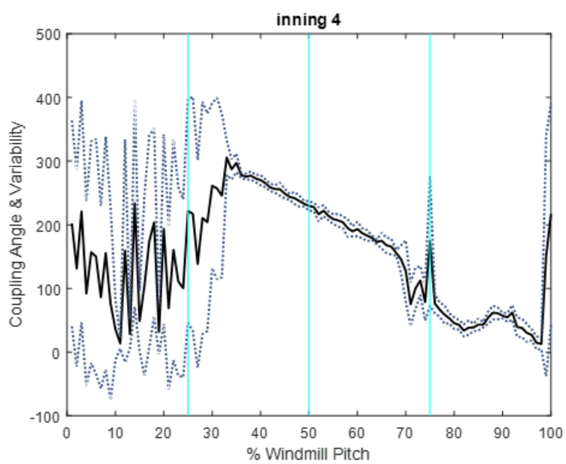
E.8 SB10 PELVIS V TORSO

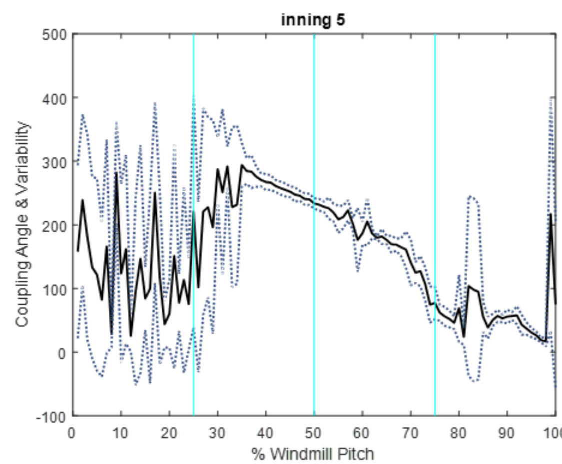


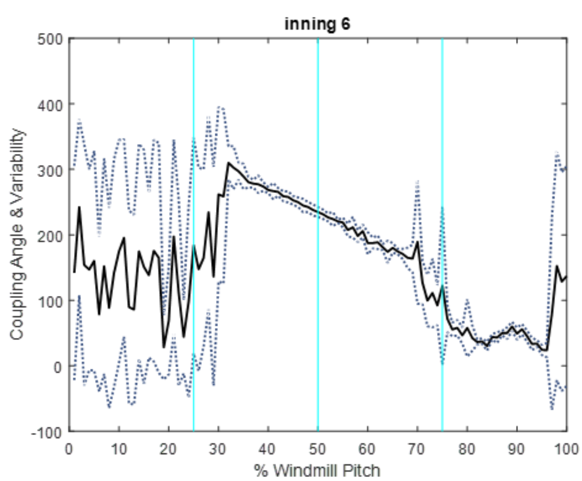


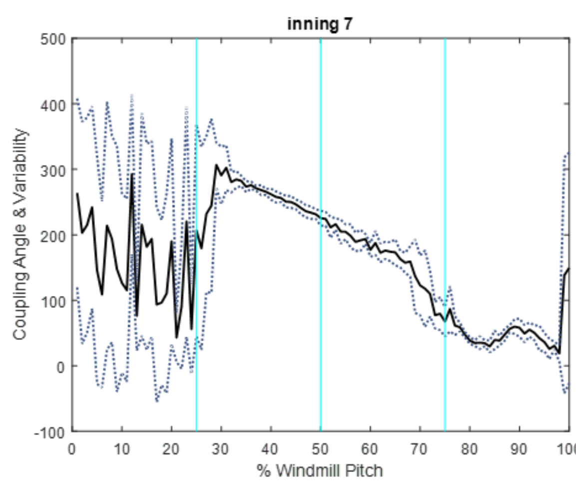

inning 2
Coupling Angle & Variability
% Windmill Pitch


inning 3
Coupling Angle & Variability
% Windmill Pitch


inning 4
Coupling Angle & Variability
% Windmill Pitch


inning 5
Coupling Angle & Variability
% Windmill Pitch

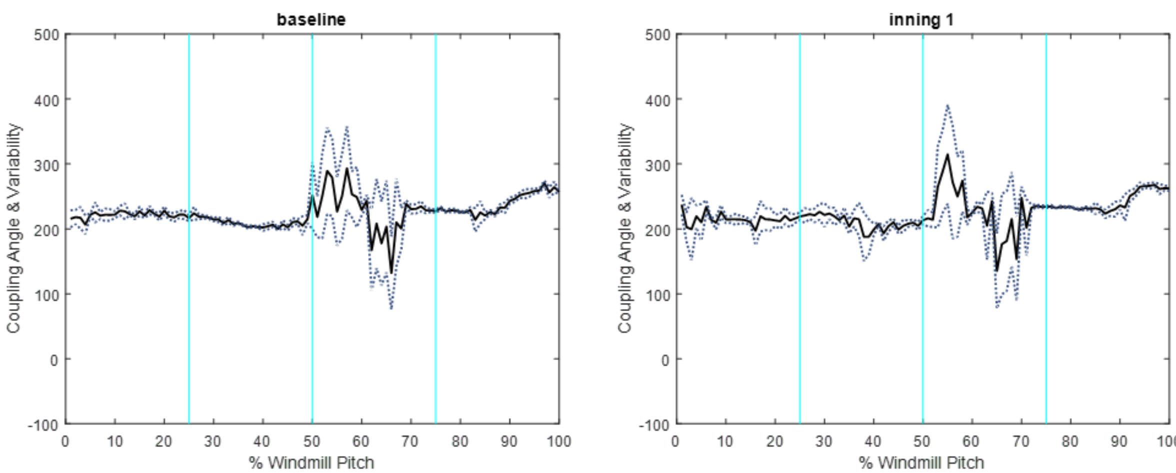

inning 6
Coupling Angle & Variability
% Windmill Pitch

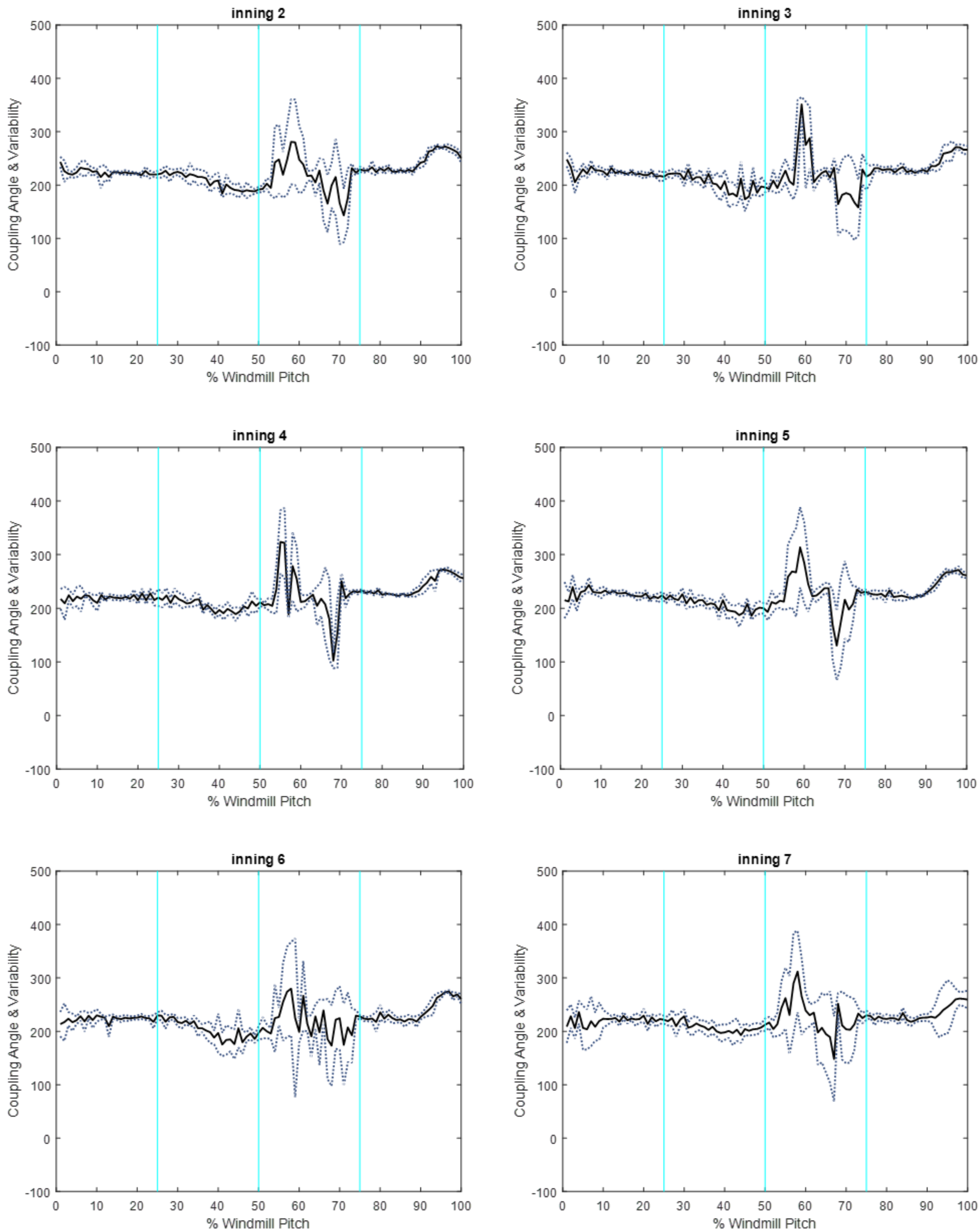

inning 7
Coupling Angle & Variability
% Windmill Pitch

APPENDIX F

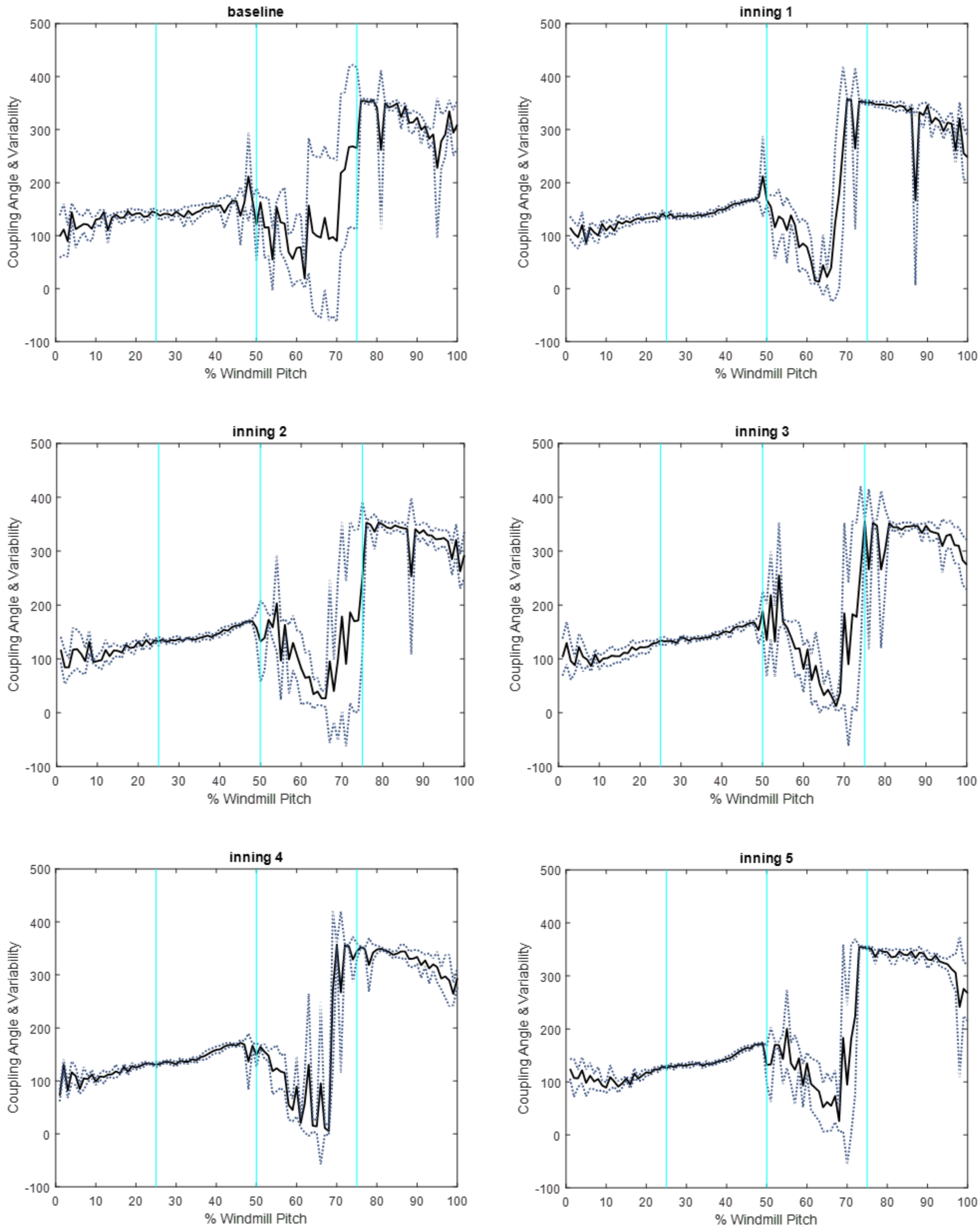
AVERAGE COUPLING ANGLE AND COUPLING ANGLE VARIABILITY OF SB05 AND SB09 FOR BASELINE AND ALL INNINGS

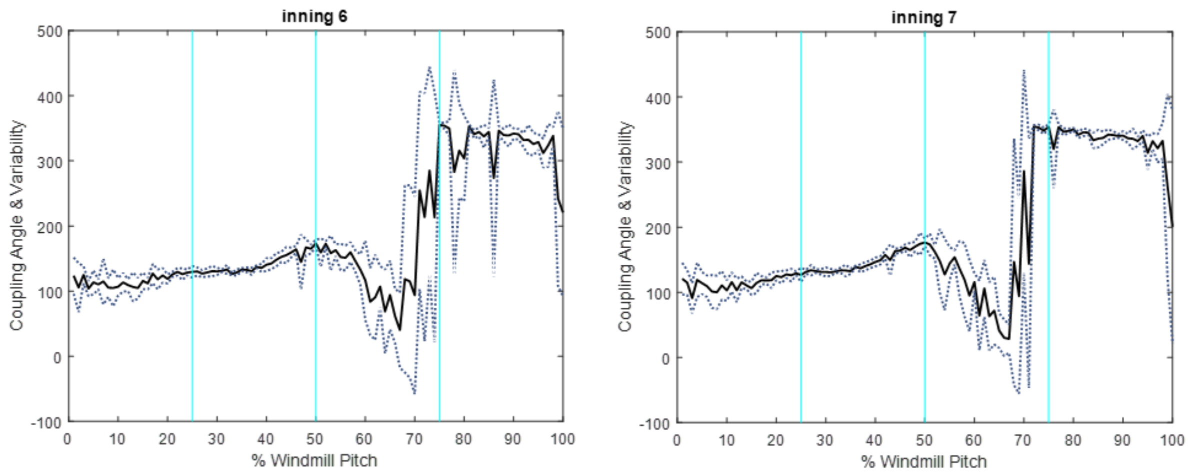
F.1 SB05 HUMERUS V FOREARM



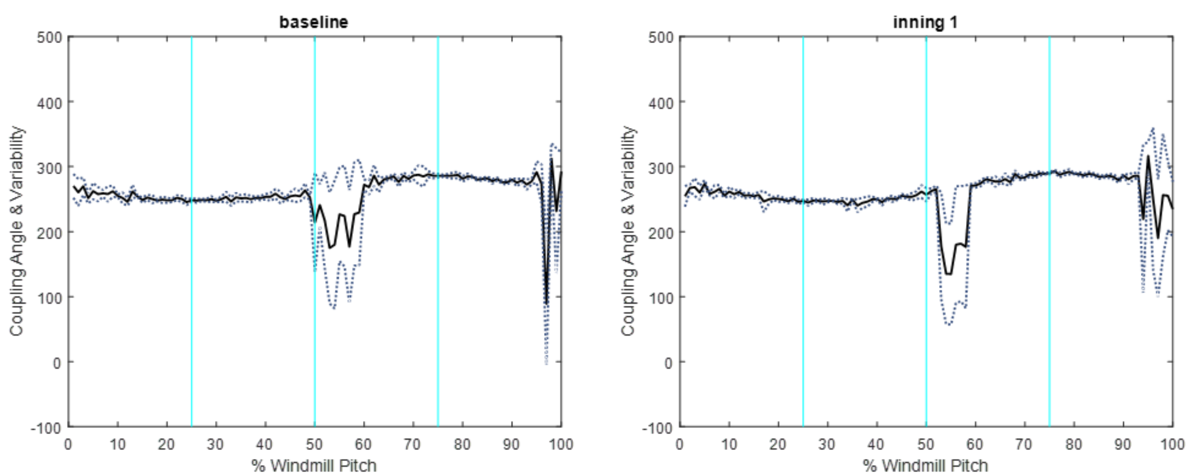

inning 2
inning 3
inning 4
inning 5
inning 6
inning 7
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0 10 20 30 40 50 60 70 80 90 100

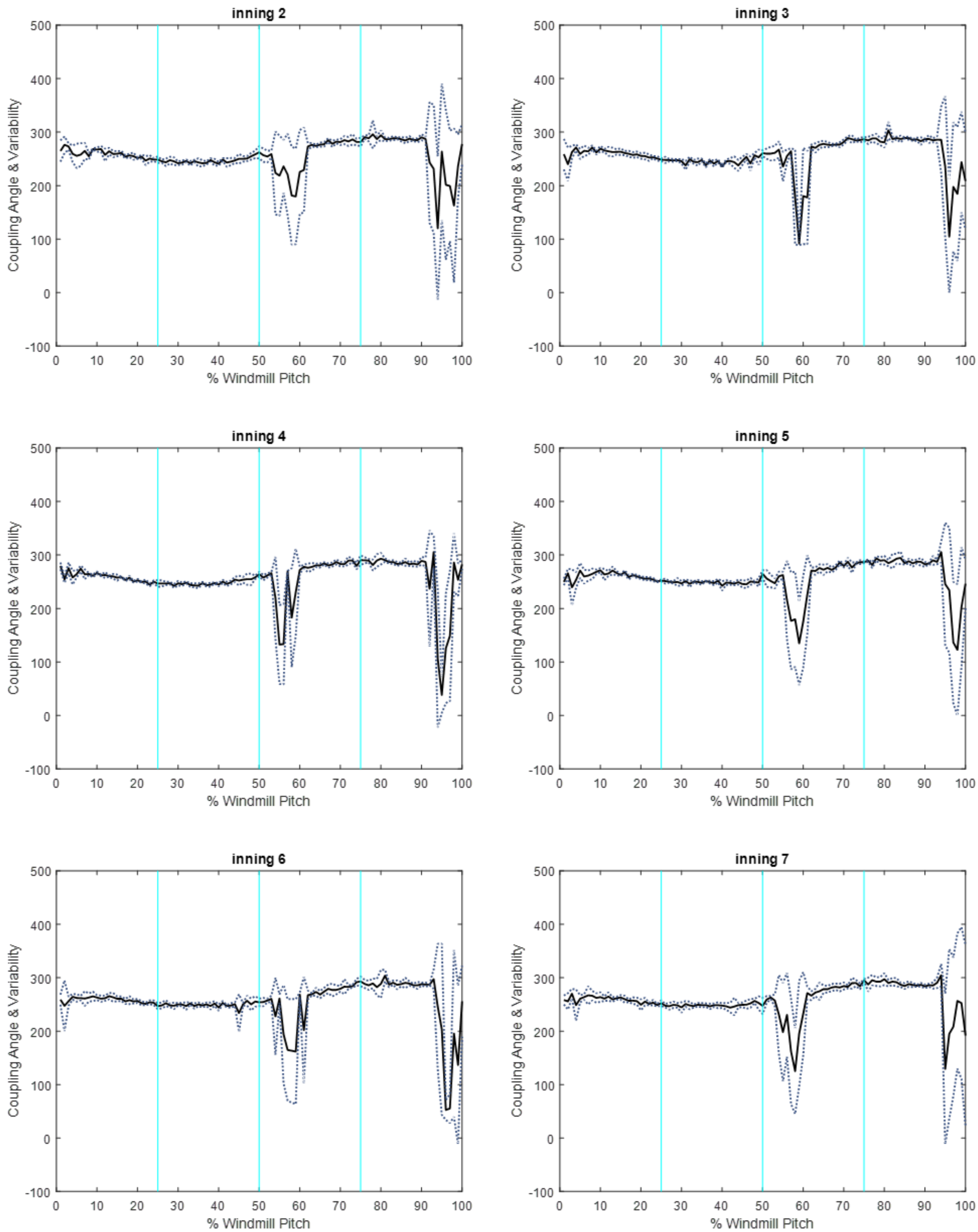
F.2 SB05 DRIVE LEG V PELVIS





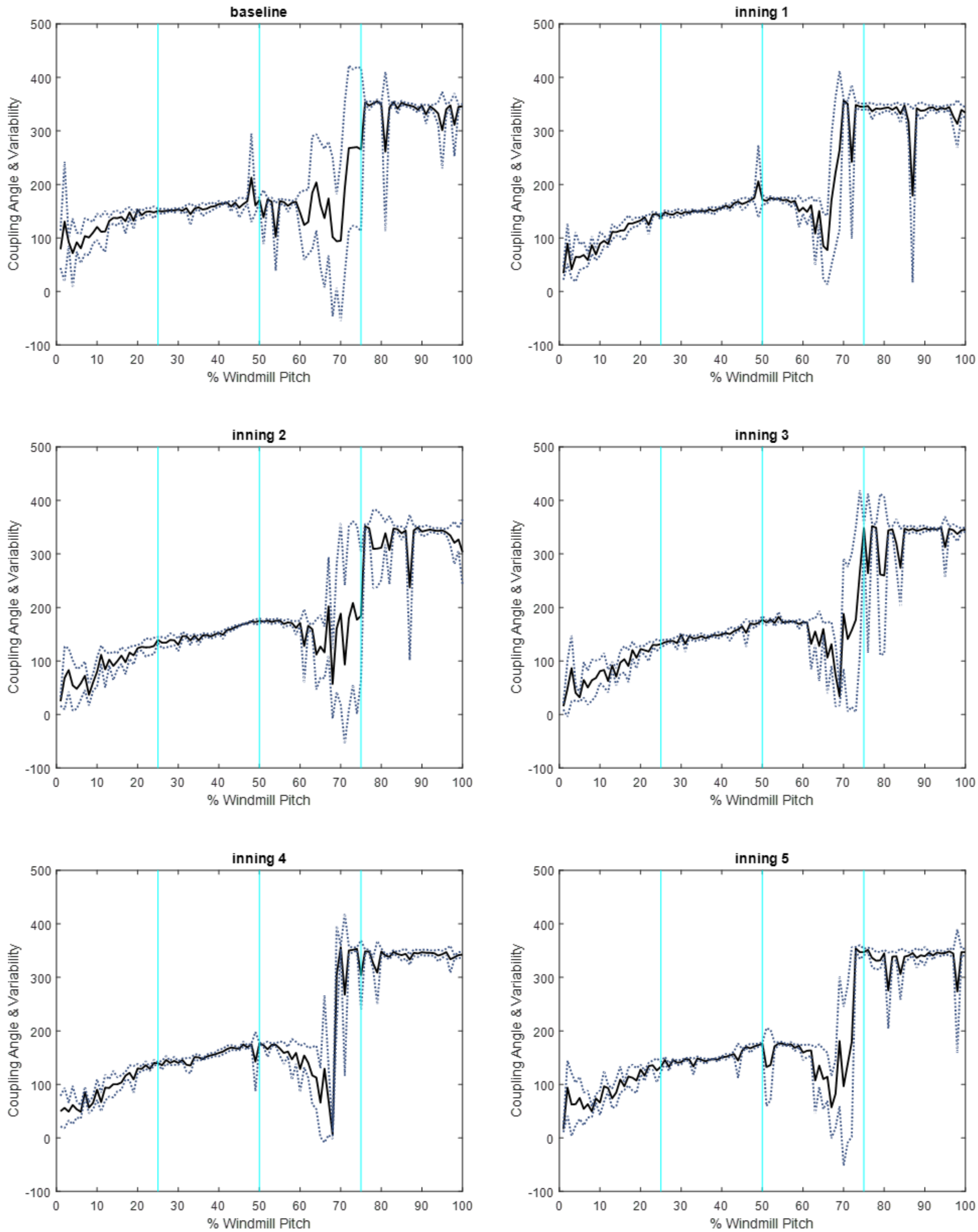
F.3 SB05 PELVIS V HUMERUS

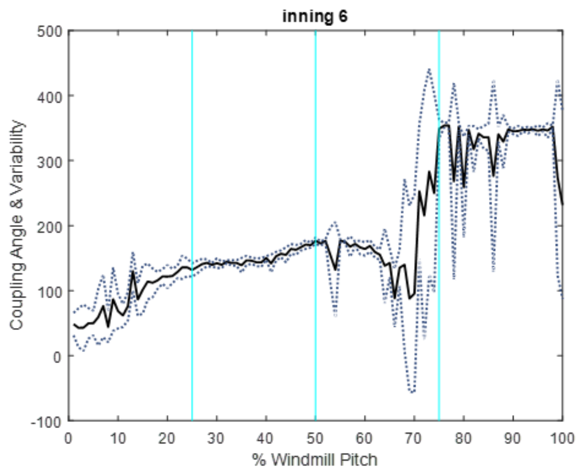


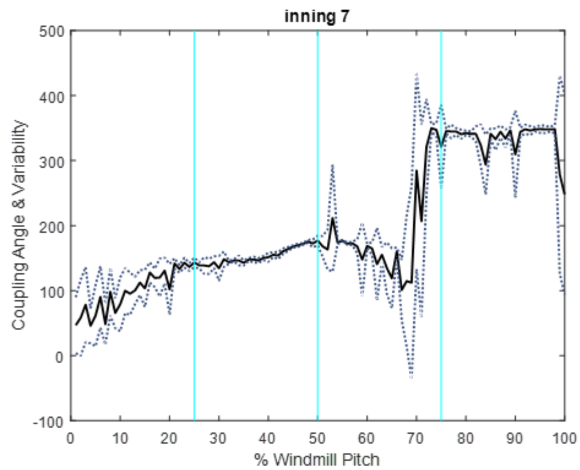


inning 2
inning 3
inning 4
inning 5
inning 6
inning 7
Coupling Angle & Variability
% Windmill Pitch

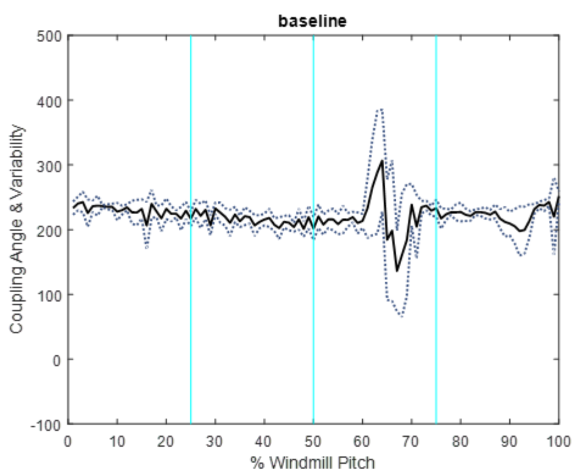
F.4 SB05 PELVIS V TORSO

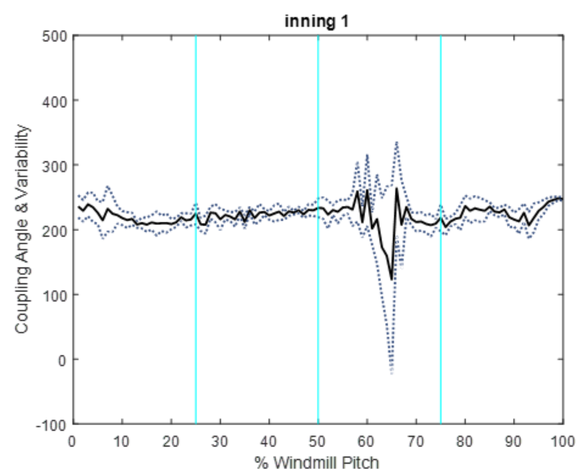


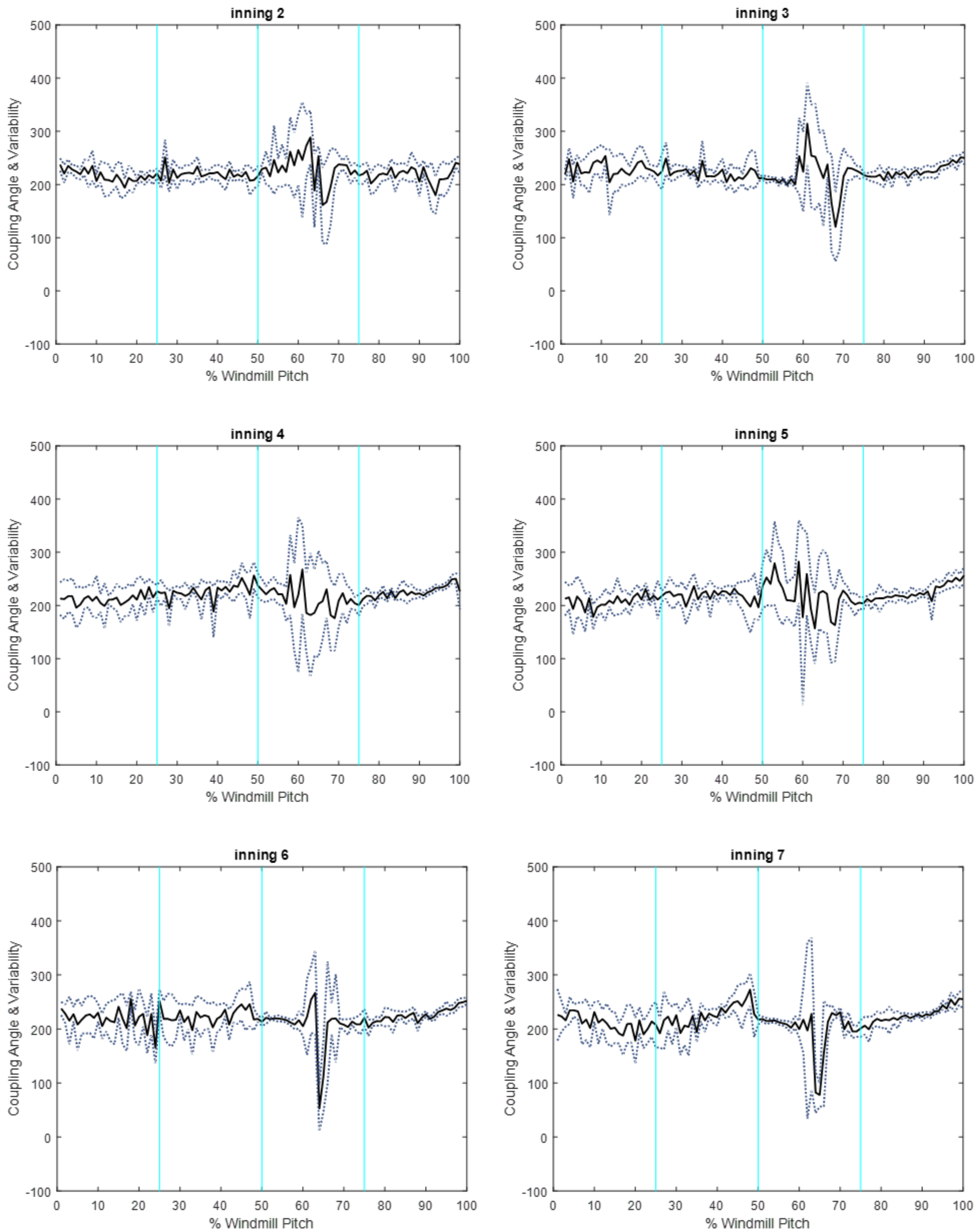




F.5 SB09 HUMERUS V FOREARM

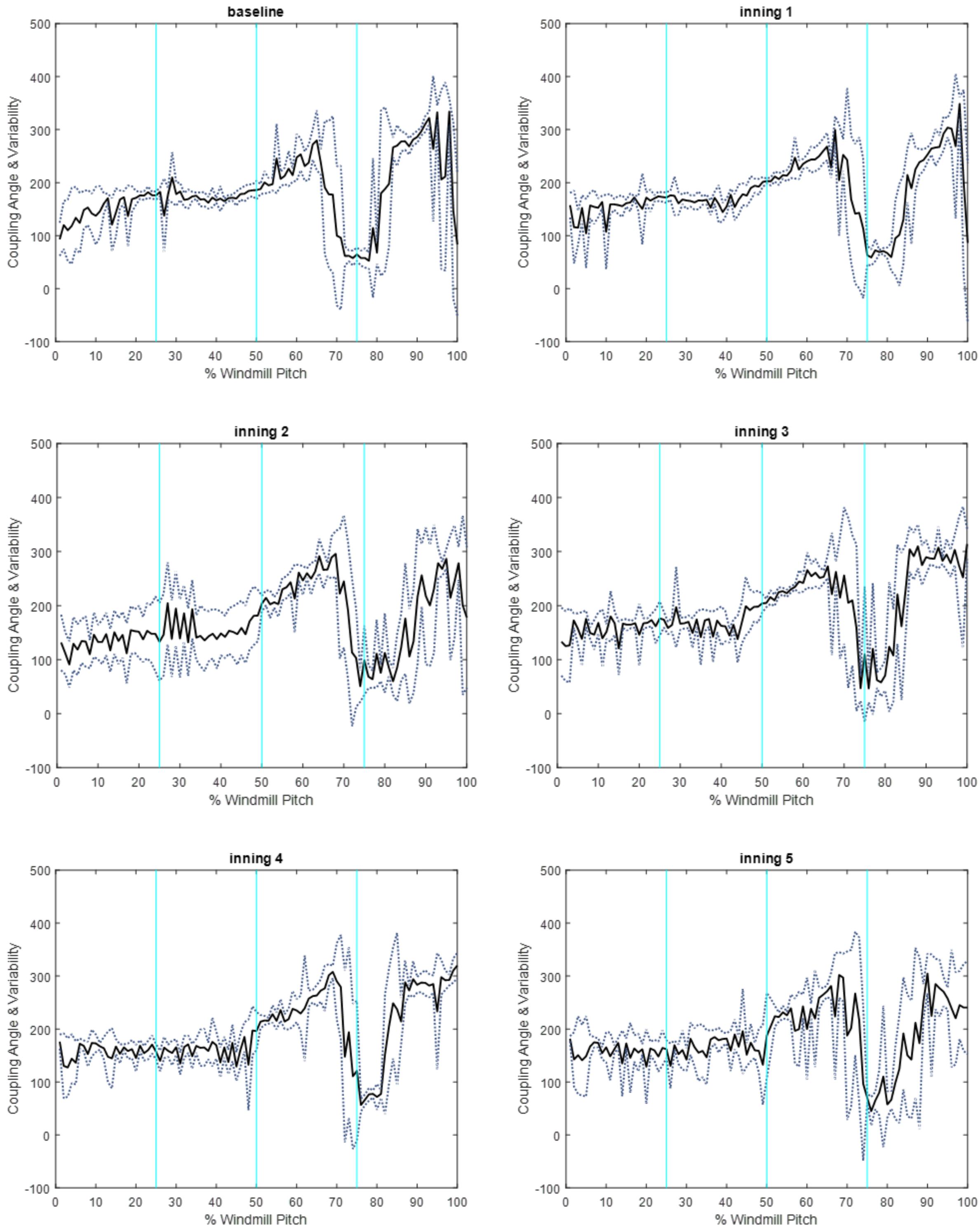


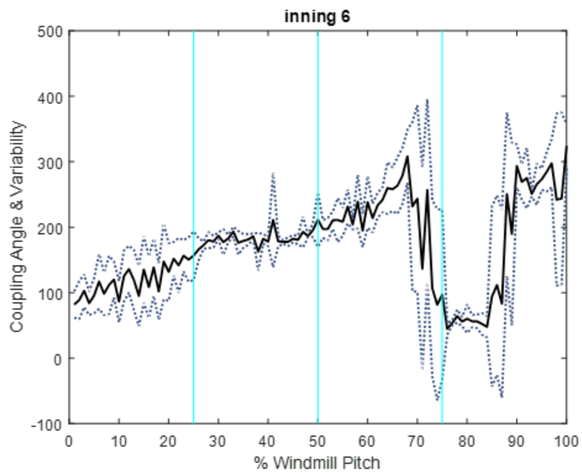


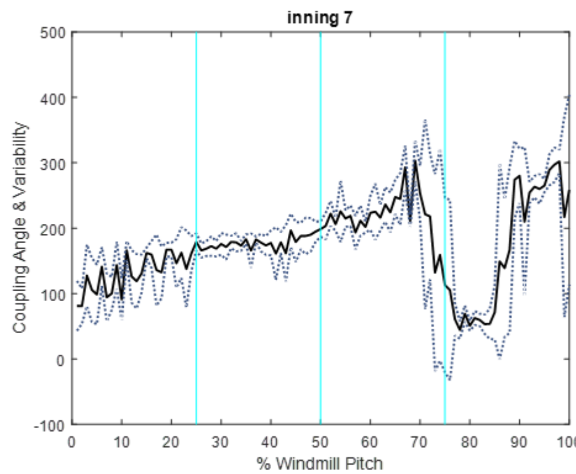


inning 2
inning 3
inning 4
inning 5
inning 6
inning 7
Coupling Angle & Variability
% Windmill Pitch

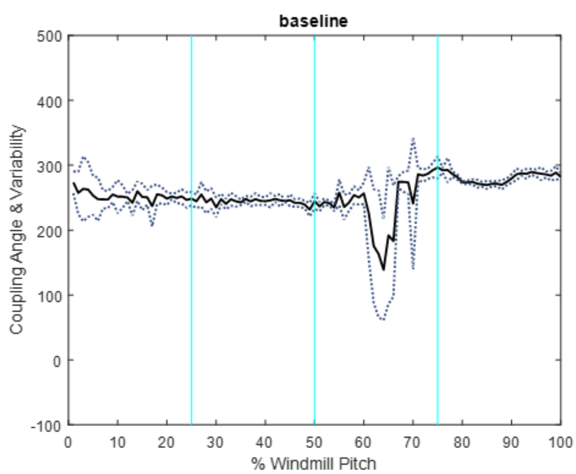
F.6 SB09 DRIVE LEG V PELVIS

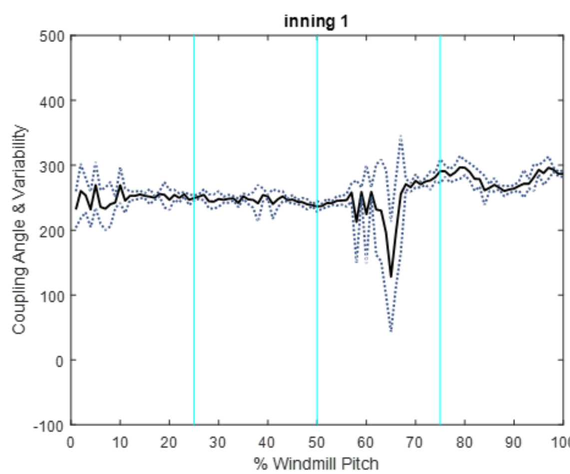


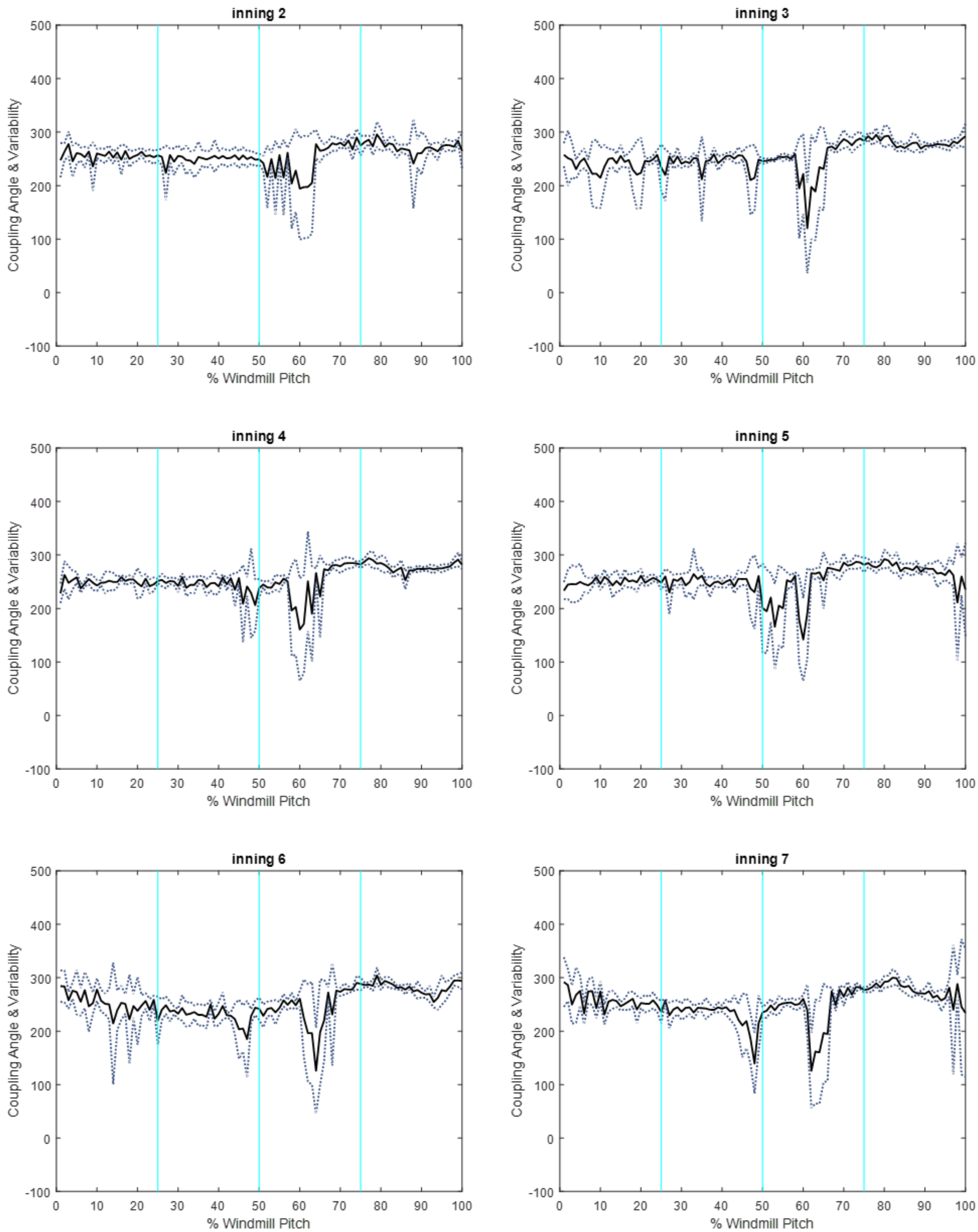




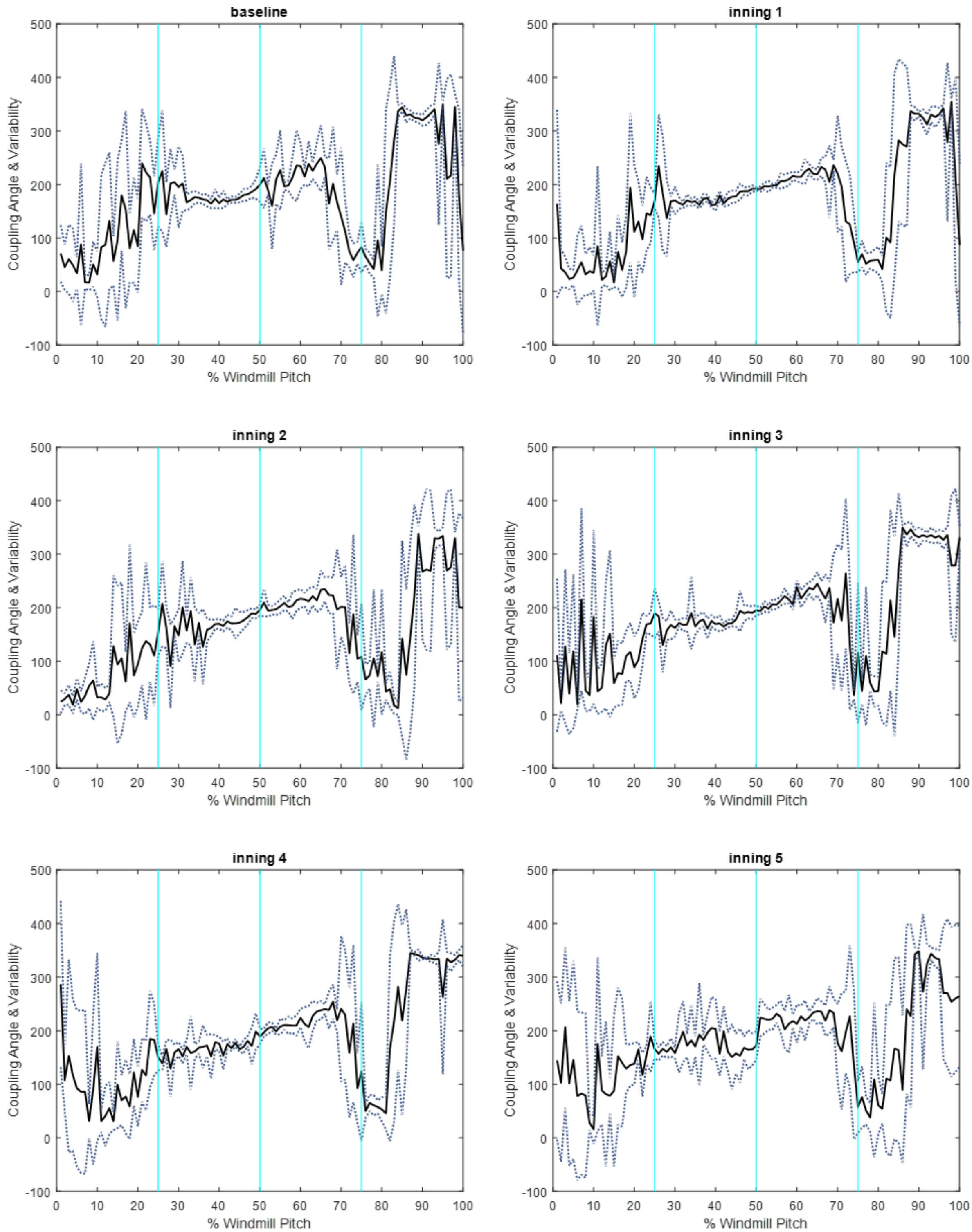
F.7 SB09 PELVIS V HUMERUS

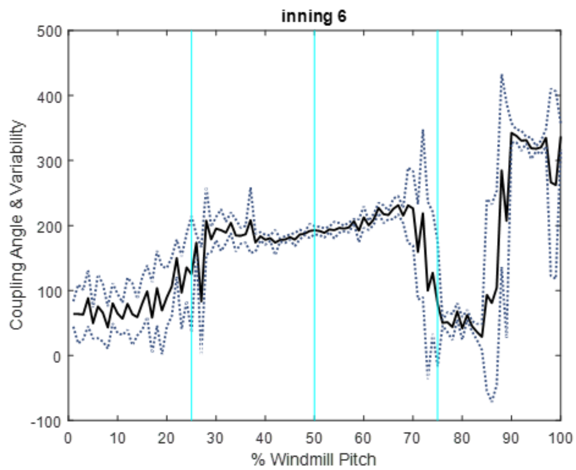


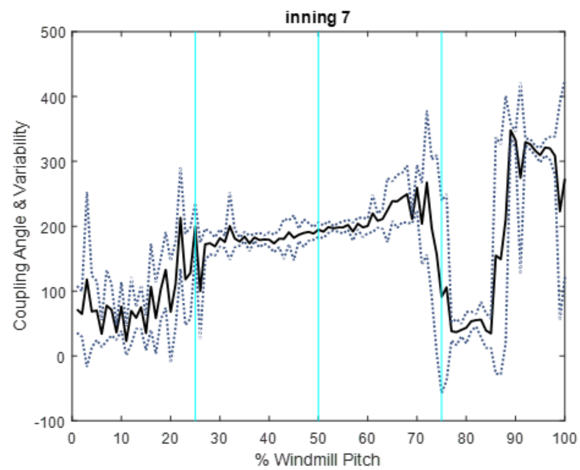



inning 2
inning 3
inning 4
inning 5
inning 6
inning 7
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0
10
20
30
40
50
60
70
80
90
100

F.8 SB09 PELVIS V TORSO




inning 6
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0
10
20
30
40
50
60
70
80
90
100


inning 7
Coupling Angle & Variability
% Windmill Pitch
500
400
300
200
100
0
-100
0
10
20
30
40
50
60
70
80
90
100

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