# EFFECTS OF TRUNK MOVEMENT ON PITCHING BIOMECHANICS AND PERFORMANCE IN HIGH SCHOOL BASEBALL PITCHERS

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## ABSTRACT

SAKIKO OYAMA: Effects of Trunk Movement on Pitching Biomechanics and Performance in High School Baseball Pitchers
(Under the direction of Joseph B. Myers)

Pitching-related upper extremity injuries affect a large number of high school baseball pitchers. Therefore, it is important to develop an intervention strategy to prevent these injuries. One of the suggested risk factors for the pitching-related upper extremity injuries is an improper technique that results in an added stress on the shoulder and elbow joints. Therefore, the purpose of the study was to examine the effects of selected pitching technique parameters on joint loading, performance, and overall quality of pitching technique, by focusing on the *observable* technical errors of the trunk. The specific technical errors examined were: 1) open shoulder, 2) backward lean at stride foot contact, 3) lateral lean at stride foot contact, 4) lateral lean at maximal shoulder external rotation (LLMER), and 5) inadequate forward trunk tilt at ball release. The pitching biomechanics of 73 high school baseball pitchers were captured using a motion capture system, two high speed cameras, and a radar gun. The presence of each error was determined by the raters who reviewed the pitching trial videos. The joint loading, performance, and quality of pitching technique were compared between the pitchers who did and did not demonstrate each error. We observed that the pitchers with LLMER demonstrated a higher ball speed but also experienced an increased joint loading at the shoulder and elbow joints. This suggests that LLMER is a strategy that pitchers take in order to achieve a higher ball speed at an expense

of increased joint loading. Additionally, there was a trend that an inadequate (<25°) and excessive (>45°) forward trunk tilt (FTT) angle at the ball release may influence the joint loading that are linked to injuries. These technical errors should be avoided considering the negative consequences of injuries. Since these technical parameters can be observed using video cameras, screening of pitching technique can be used to identify pitchers with these technical errors. Possible strategies to modify LLMER and FTT angle at ball release were also identified. Using these strategies, it may be possible to correct the technical errors and thereby prevent the pitching-related upper extremity injuries.

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# CHAPTER I

# INTRODUCTION

## 1.1 Pitching-related Upper Extremity Injuries

It has been estimated that approximately 73-79% of all injuries occurring in baseball are associated with pitching.[39, 49, 133] Most of these injuries occur in the upper extremity joints, and impact an pitcher's ability to continue participation.[49, 108, 133] While the injury rate in baseball is low compared to the other sports, it needs to be highlighted that approximately 25% of the baseball injuries result in more than 21 days lost from sport,[49, 133] and that approximately 10% of the injuries in baseball result in a surgical intervention.[108] Furthermore, the number of high school pitchers who sustain shoulder or elbow injuries that require surgery is on the rise.[154] The American Sports Medicine Institute reported that there was a 6-fold increase in the number of surgical cases on high school baseball pitchers between 1994-1999 and 2000-2004 periods.[154] Therefore, development of strategies to prevent pitching-related upper extremity injury in young competitive pitchers is needed.

It is theorized that the pitching-related upper extremity injuries are linked to extrinsic participation factors (ex. pitch count),[68, 126, 127, 154, 161] suboptimal physical characteristics (ex. strength and joint range of motion),[33, 51, 116, 138, 143, 175, 190] and faulty pitching techniques that place high stress on the upper extremity joints.[7, 8, 18, 44] This theoretical framework provides three potential approaches to preventing pitching-related upper extremity injures: 1) regulation of unsafe participation factors, 2) exercise intervention to modify suboptimal

physical characteristics, and 3) instructional intervention to correct improper pitching techniques. Over the past decades, advancements in our understanding of the extrinsic participation factors and physical characteristics that are linked to injuries have lead to instatement of pitch count regulations in Little League baseball[15, 126, 127] and clinical recommendations of various exercises that may be used to improve the suboptimal physical characteristics.[26, 104, 117, 145, 155, 156, 172, 186] However, the approach to prevent injuries through identification of pitching techniques that are associated with increased joint loading has received little attention to date and is an area for much needed exploration.[18]

### 1.2 Pitching Biomechanics and Injury

Pitching is a highly dynamic task that requires coordination of the upper extremity, lower extremity, and the trunk segments.[7, 8, 70, 165, 166] Conventionally, pitching is divided into 6 phases: wind up, stride, arm-cocking, acceleration, deceleration, and follow through (**Figure 1**).

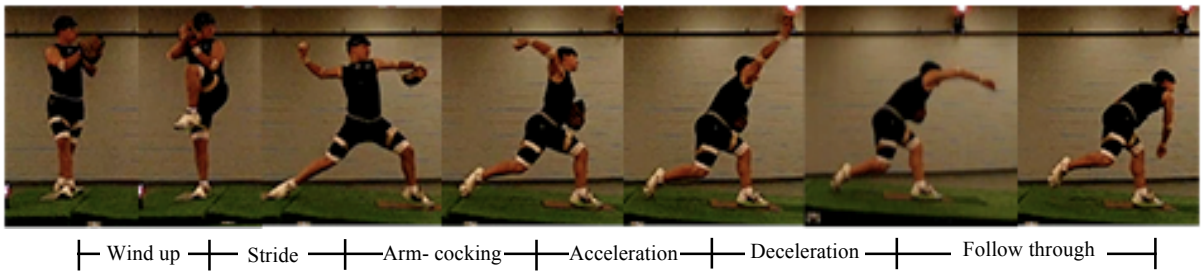



**Figure 1**. Six phases of pitching motion

Of these phases, the arm-cocking and acceleration phases are the two most dynamic phases when the shoulder and elbow joints experience the highest magnitude of loads that are directly linked to variety of upper extremity injuries.[50, 69, 70, 176, 198] The arm cocking phase

starts at the stride foot contact and ends with the achievement of the maximal shoulder external rotation, and the acceleration phase starts at the maximal shoulder external rotation and ends at ball release. Specifically, the internal elbow varus moment that peaks at the end of the arm-cocking phase has been linked to injuries to the ulnar collateral ligament, flexor pronator mass, ulnar nerve, and osseous structures that stabilize the joint.[9, 122, 139-141, 178, 198] At the shoulder, the internal rotation moment and anterior force that peak during the arm cocking phase, and the proximal force that resists joint distraction during the acceleration phase have been linked to injuries to the rotator cuff and biceps-labral complex.[14, 70, 110, 164, 215] While the pitchers' upper extremity joints are capable of withstanding such loads under normal circumstances, performing repetitive pitches using a technique that places additional stress on the joints may lead to a gradual attenuation of the soft tissue structures, and ultimately injury.[44] Therefore, identifying movement patterns that are associated with increased joint loading may lead to identification of pitchers who may be at a higher risk of injury, and development of strategies to prevent pitching-related upper extremity injuries.

Over the past decades, the use of laboratory-based motion capture systems has lead to identification of various three-dimensional kinematic and kinetic variables during pitching that are associated with increased joint loading.[8, 44, 64, 178, 199, 201, 203, 206] Identification of these variables helped us better understand the effects of pitching technique on joint loading, and the relationships among the biomechanical parameters. However, a major limitation of this approach is a difficulty in transferring the study observations to clinical applications, since motion capture systems are rarely available to baseball coaches, parents, and players.[44]

Recognizing this limitation, a recent study by Davis et al[44] took a different approach and investigated whether the observable technical errors that are commonly identified by

baseball coaches are associated with the injurious joint loading. The technical errors are specific movement patterns during pitching that are considered to limit pitcher's performance and/or increase the loads placed on the pitcher's joints. These technical errors are often based on an empirical evidence gathered by a number of baseball coaches, and are identified through repeated observations.[44, 94, 95, 147] The advantage of taking this approach is that once the technical errors that are associated with increased joint loading are identified, baseball coaches, parents, and sports medicine clinicians can identify pitchers who may be at an increased risk of injury. Once these pitchers are identified, instructions to correct the technique may help decrease the joint loading and possibly prevent pitching-related upper extremity injuries. Since the study by Davis et al[44] is the only study that has taken this approach to date, more studies that are based on this study are needed.

While there are many technical errors that coaches look for when evaluating a pitching technique, experienced pitching coaches recommend identifying and correcting the technical errors of the trunk before addressing the others, because a proper movement of the trunk is considered a prerequisite for the proper upper extremity movement.[94, 95] This notion is supported by the fact that the trunk is a proximal base for the upper extremity segments, and therefore the kinematics of the trunk segment have a direct influence on the upper extremity kinematics and kinetics.[7, 8, 89, 158, 165, 166]

These technical errors are often identified at critical time points during a pitching motion: stride foot contact, maximal shoulder external rotation, and ball release). During pitching, a rapid trunk movement is initiated after stride foot contact, when the forward linear momentum generated by the lower extremity is transferred to the upper body.[188, 206] At stride foot contact, a pitcher's upper torso is aligned parallel to the direction of throw, and the trunk

is in a vertical alignment between the stance and the stride feet.[50, 94, 95, 159] At this critical time point, common technical errors of the trunk include "open shoulder", "backward lean" and "lateral lean". The open shoulder (OS) is an error characterized by the anterior aspect of the leading shoulder being visible to the target at stride foot contact, as a result of initiation of upper torso rotation before the stride foot contact (**Figure 2**). The backward lean at stride foot contact (BLSFC) is characterized by a failure to maintain the head and upper torso vertically over the front foot in a sagittal plane (**Figure 3**), and lateral lean at stride foot contact (LLSFC) is characterized by a failure to maintain the head over the umbilicus in a frontal plane (**Figure 4**). [7, 8, 44, 94, 95]

After stride foot contact, the upper torso rapidly rotates and translates linearly towards the target while hyperextension of the trunk maintains the upper torso in an upright orientation.[50, 94, 95, 159] As the shoulder reaches the maximal external rotation, the upper torso becomes squared with the target. A common technical error at the instant of maximal shoulder external rotation is a failure to maintain the head balanced over the front foot as a result of an excessive lateral leaning towards the non-throwing shoulder (LLMER) (**Figure 5**). Once the throwing shoulder reaches the maximal external rotation, the upper torso flexes forward and laterally towards the non-throwing shoulder before ball release.[50, 94, 95, 159] A failure to adequately tilt the trunk forward towards the target at ball release (**Figure 6**) is considered a technical error.[7, 8, 44, 94, 95]

Baseball coaches consider that these technical errors of the trunk place additional stress on the shoulder and elbow joints and/or are associated with ineffective use of trunk in generating ball speed.[94, 95] Since ineffective use of trunk motion has been theorized to increased the reliance on the upper extremity joints, it may also indirectly increase the stress

placed on the anatomical structures surrounding shoulder and elbow joints.[7, 8, 44] In addition to the potential effects on joint loading and ball speed, the technical errors of the trunk may negatively influence the pitch accuracy and an overall impression or quality of pitching technique, as they are associated with "poor" pitching techniques.[94, 95]

### 1.3 Statement of Purpose

The purpose of the study is to determine the effects of the technical errors of the trunk (**Figures 2-6**) on joint loading, performance, and quality of pitching technique (assessed using the modified pitching assessment form developed by the American Sports Medicine Institute (**Appendix 1**)) in high school baseball pitchers. We will address this aim by comparing the upper extremity joint loading, ball speed, accuracy, and quality of pitching technique 1) between the pitchers who demonstrate the technical errors at 0, 1, and 2 or more critical time points (*cumulative effects of the technical error*), and 2) between the pitchers who demonstrate the technical errors at each critical time point (stride foot contact, maximal shoulder external rotation, and ball release), and the pitchers who do not demonstrate the technical errors at any time point (*effects of the technical errors at each critical time point*). If one or more of the technical errors are associated with an increased joint loading, upper extremity and upper torso kinematics will be compared between the pitchers with and without the technical errors to understand how these pitchers pitch differently, and to identify potential strategies to modify the technical errors.

The observations from this study may validate the importance of having a proper trunk movement during pitching, and identification of potential risk factors that can be detected by coaches, parents, and sports medicine clinicians. Detection of such errors would help us identify pitchers who may be at a higher risk of injury in the community setting. The

study will also provide a foundation for future studies that attempt to prevent pitching-related upper extremity injuries through modification of a pitching technique.

### 1.4 Operational Definitions

- *High school pitchers*: Individuals between the ages of 13-18 who have been pitching for a minimum of 2 seasons as a starter or a relief/bullpen pitcher.[147]
- *Critical time points*: Time points during pitching with biomechanical significance
    - *Stride foot contact*: The first instant when any part of the stride foot contacts the ground. This instant marks the beginning of the arm-cocking phase.
    - *Maximal shoulder external rotation*: The instant the throwing shoulder reaches the maximal external rotation. This instant marks the end of the arm-cocking phase, and the beginning of the acceleration phase. The elbow varus and shoulder internal rotation moments peak around this time point.
    - *Ball release*: The instant the ball becomes separated from the hand. This instant marks the end of the acceleration phase. The shoulder and elbow proximal forces peak around this time point.
- *Technical errors*: Specific movement patterns observed at the critical time points that are considered to limit the pitcher's performance and/or increase the loads placed on the pitcher's joints based on an empirical evidence gathered by a number of baseball coaches.[94, 95]
    - At stride foot contact:
        - *Open shoulder (OS):* A common technical error that is characterized by a premature upper torso rotation, and having the anterior aspect of the leading shoulder facing the target at stride foot contact. (**Figure 2**)

        - *Lateral trunk lean (LLSFC):* A common technical error at stride foot contact that is characterized by a lateral trunk lean towards the stance leg, resulting in pitcher's head and upper torso not being vertically aligned over the umbilicus (**Figure 3**)
        - *Backward trunk lean (BLSFC)*: A common technical error at stride foot contact that is characterized by a backward trunk lean, resulting in pitcher's head being positioned behind the vertical line passing through the stride foot (ankle) (**Figure 4**).
    - At maximal shoulder external rotation
        - *Lateral trunk lean (LLMER)*: A common technical error at the instant of maximal shoulder external rotation that is characterized by a lateral trunk lean towards the non-throwing shoulder, resulting in lateral deviation of the pitcher's head from the vertical line passing through the stride foot (ankle) by more than a head width (**Figure 5**).
    - At ball release
        - *Inadequate forward trunk flexion (FT)*: A common technical error that is characterized by the mid-line of the trunk forward tilted less than 20° at ball release (**Figure 6**).

- *Quality of pitching technique*: Quality of pitching technique evaluated using the modified version (**Appendix 1**) of the qualitative assessment tool developed by the American Sports Medicine Institute (**Appendix 2**).[126, 147]
- *Ball Speed:* Average of the three fastest strike pitches

- *Accuracy*: The average distance between the "X" on the target and the location of the ball as it hits the target from the first 5 qualifying pitches

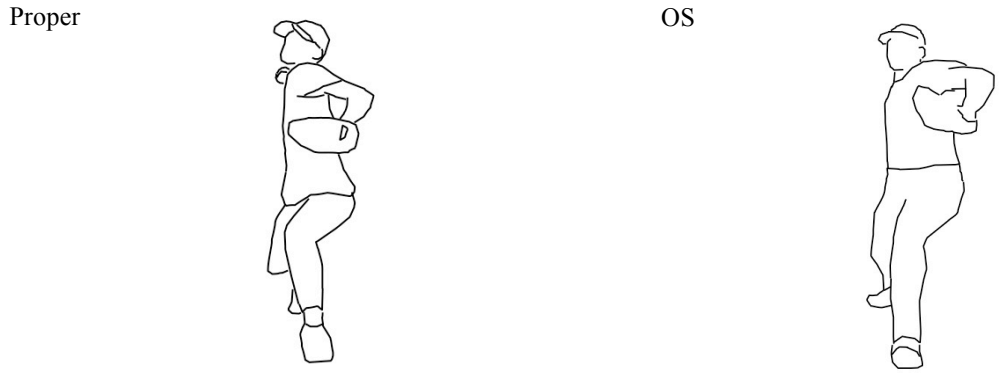



**Figure 2**. Open Shoulder (OS): The anterior aspect of the leading shoulder is facing the target at stride foot contact.

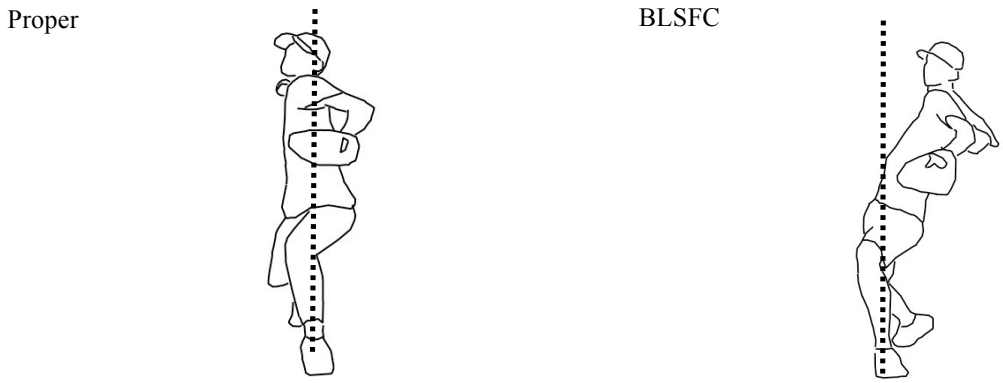



**Figure 3**. Backward lean at stride foot contact (BLSFC): Pitcher's head is positioned behind the vertical line passing through the front foot (ankle) at stride foot contact.

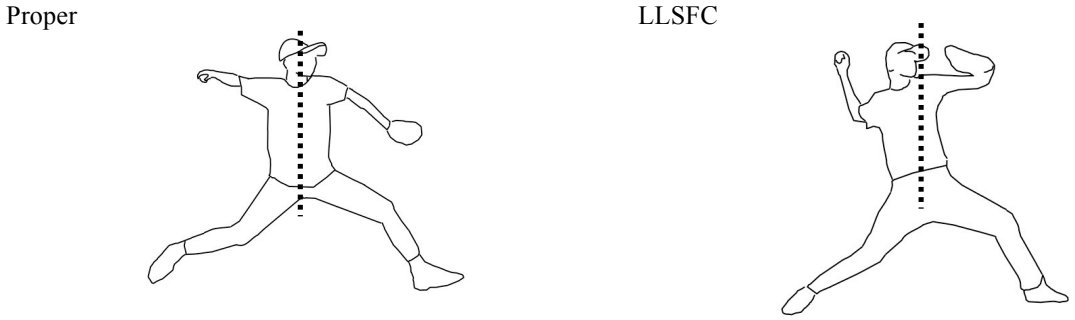


**Figure 4**. Lateral lean at stride foot contact (LLSFC): Pitcher's head is positioned behind the vertical line passing through the umbilicus.

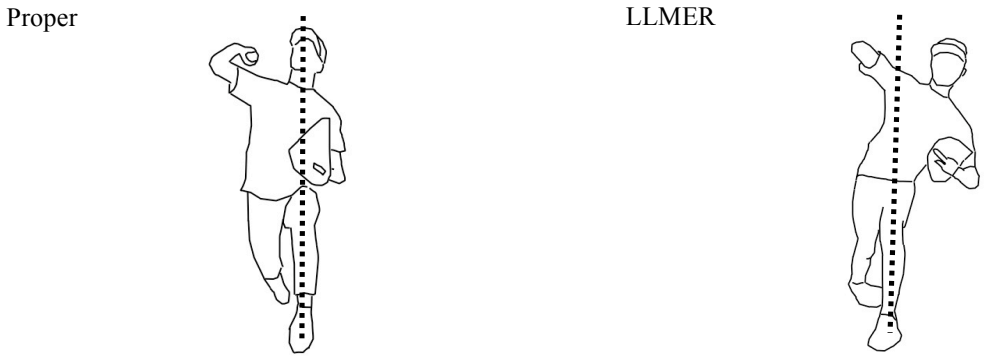



**Figure 5**. Lateral lean at maximal shoulder external rotation (LLMER): Pitcher's head is deviated from the vertical line passing through the stride foot (ankle) by more than a head width at maximal shoulder external rotation.

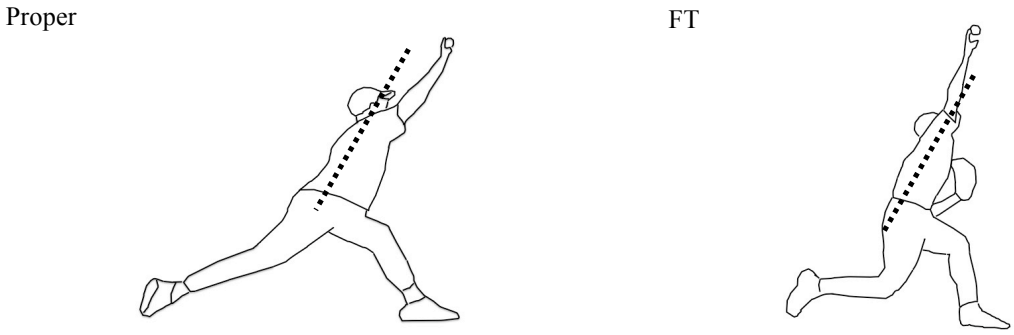



**Figure 6**. Inadequate forward trunk tilt at ball release (FT): The line passing through mid-trunk is tilted less than 20° from vertical at the ball.

### 1.5 Specific Aims (*original*)

**Specific Aim 1**: To compare the (a) upper extremity joint kinetic variables (peak shoulder proximal force, peak shoulder internal rotation moment, and peak elbow varus moment), (b) ball speed, (c) accuracy, and (d) quality of pitching technique between the high school pitchers who demonstrated the technical errors at the critical time points (stride foot contact:

OS, BLSFC, or LLSFC, maximal shoulder external rotation: LLMER, and ball release: FT) and the pitchers who did not demonstrate the technical errors at any critical time point.

**Hypothesis 1:** The pitchers with the technical errors at each critical time point will demonstrate (a) greater joint loading, (b) lower ball speed, (c) lower accuracy, and (d) lower quality of the pitching technique compared to the pitchers who do not demonstrate the technical errors at any critical time point.

**Specific Aim 2:** To compare the (a) upper extremity joint kinetic variables (peak shoulder proximal force, peak shoulder internal rotation moment, and peak elbow varus moment), (b) ball speed, (c) accuracy, and (d) quality of pitching technique between the high school pitchers who demonstrate the technical errors at 0, 1, 2, and 3 critical time points.

**Hypothesis 2:** The pitchers who demonstrate the technical errors at a greater number of time points will demonstrate (a) greater joint loading, (b) lower ball speed, (c) lower accuracy, and (d) lower quality of pitching technique.

Additionally, if one or more of the technical errors are associated with an increased joint loading (based on the observations from the specific aim 1), upper extremity and upper torso kinematics (**Table 2**) will be compared between the pitchers with and without the technical errors to understand how these pitchers pitch differently, and to identify potential strategies to modify the technical errors.

### 1.6 Independent variables

Specific Aim 1

- A presence of the technical errors at the critical time points (**Table 1**)
    - Stride foot contact (open shoulder, lateral lean, or backward lean)
    - Maximal shoulder external rotation (lateral lean)
    - Ball release (inadequate forward trunk lean)

Specific Aim 2

- A number of the critical time points with technical errors
    - 0
    - 1
    - 2 or more

### 1.7 Dependent variables

- Upper extremity joint kinetic variables (**Table 1**)
- Ball speed
- Accuracy
- Quality of pitching technique
- Upper extremity and trunk kinematic variables (**Table 2**)*

  ** These variables will be examined when the technical errors are associated with increased joint loading.*

**TABLE 1**: Upper extremity joint kinetic variables

| **TABLE 1** |
| --- |
| Peak shoulder proximal force (% body weight) |
| Peak shoulder internal rotation moment (% body weight*height) |
| Peak elbow varus moment (% body weight*height) |

**TABLE 2:** Upper extremity and trunk kinematic variables

| **TABLE 2** |
| --- |
| Stride foot contact |
| Pelvis rotation angle (°) |
| Upper torso rotation angle (°) |
| Upper torso lateral flexion angle (°) |
| Upper torso forward flexion angle (°) |
| Maximal shoulder external rotation |
| Upper torso rotation angle (°) |
| Upper torso lateral flexion angle (°) |
| Upper torso forward flexion angle (°) |
| Shoulder external rotation angle (°) |
| Shoulder horizontal abduction angle (°) |
| Shoulder elevation angle (°) |
| Elbow extension angle (°) |
| Ball release |
| Upper torso rotation angle (°) |
| Upper torso lateral flexion angle (°) |
| Upper torso forward flexion angle (°) |
| Shoulder horizontal abduction angle (°) |
| Shoulder elevation angle (°) |
| Elbow extension angle (°) |
| Peak velocity |
| Upper torso rotation velocity (°/sec) |
| Shoulder horizontal adduction velocity (°/sec) |
| Shoulder internal rotation velocity (°/sec) |
| Elbow extension velocity (°/sec) |
| Temporal variables |
| Initiation of upper torso rotation (%) |
| Maximal shoulder external rotation (%) |

## 1.8 Limitations

- The movement of the scapula will not be considered in the analysis of shoulder movement

## 1.9 Delimitation

- Only the overhand pitchers will be included in the study, since inclusions of the sidearm and underarm (submarine) pitchers will introduce a significant variability in the data
- An analysis of pitching technique will be limited to fast pitches performed from a wind up
- Pitching technique will be assessed in a controlled laboratory setting to avoid extraneous distraction from the external environment

## 1.10 Assumptions

- Subjects will provide their maximal effort during the data collection
- Adequate warm up will be achieved prior to the data collection
- Performance of 25-35 pitches will not induce fatigue that alters the pitcher's technique

# CHAPTER II

# LITERATURE REVIEW

## 2.1 Introduction

As more and more high school pitchers are sustaining severe injuries that require prolonged time loss from sports, investigation of strategies to prevent these injuries is needed.[154] Based on the literature review, three potential approaches to preventing pitching-related upper extremity injures are 1) regulation of the participation factors, 2) exercise intervention to modify the physical characteristics that are associated with injures, and 3) instructional intervention to modify the pitching techniques that are linked to high joint loads. While the first (participation factor) and the second (physical characteristics) approaches have been explored over the past decade, and will continue to be explored in the future, no study to date have attempted to intervene on the pitching technique to prevent pitching-related upper extremity injuries (the third approach).

The purpose of the study is to determine the effects of the technical errors of the trunk at the critical time points (stride foot contact, maximal shoulder external rotation, and ball release) (**Table 1**) on joint loading, performance, and quality of pitching technique in high school pitchers. This literature review provides the background and rationale for this study by discussing the epidemiology and etiologies of the pitching-related upper extremity injures, and current understanding of the pitching biomechanics. In addition, methodological considerations will be discussed.

## 2.2 Pitching-Related Upper Extremity Injuries

### *2.2.1 Epidemiology*

Baseball is a relatively safe sport in terms of injury rates reported in the literature.[49, 106, 108, 133] The reported injury rates in baseball range from 0.17 to 5.83 injures per 1000 athlete-exposure,[49, 106, 108, 133] with the older collegiate pitchers having a higher injury rate (1.9-5.83 injuries per 1000 athlete-exposure)[49, 133] compared to the younger little league and high school baseball players (0.17-2.0 injuries per 1000 athlete-exposure).[106, 108] These reported injury rates are lower compared to the injury rates in the other sports, such as football (9.6-35.9 injuries per 1000 athlete-exposure), men's hockey (2.0-16.3 injuries per 1000 athlete-exposure), soccer (4.3-18.8 injuries per 1000 athlete-exposure), and basketball (4.3-9.9 injuries per 1000 athlete-exposure).[92] However, simply looking at the injury rate may be misleading in understanding the magnitude of the problem associated with upper extremity injuries in baseball. This is because the injury rate does not reflect a large proportion of the baseball players who are affected by pain/injury, and relatively severe consequences of injuries (i.e. prolonged time loss, need for surgery, and costs).

The upper extremity injuries, which comprise more than half of all injuries occurring in baseball, affect a large number of competitive baseball players.[24, 49, 83, 108, 115, 126, 127, 133, 154, 157, 161, 171] Epidemiological studies demonstrate that approximately 32-38%[82, 83, 85, 115, 126, 127, 153, 189] and 18-69%[126, 127, 153, 189] of baseball players experience shoulder and elbow pain, respectively. In particular, pitchers are susceptible to upper extremity injuries as indicated by the higher incidences of injury reported at high school,[108] collegiate,[49, 133] and professional levels[40] when compared to position players. In high school baseball, Krajnik et al[108] reported that 73% of the injuries that resulted in surgery are sustained by pitchers.

It is estimated that 16.7% of all high school baseball players experience injury each season,[163] and that 15% of all game appearances result in shoulder and/or elbow pain in youth baseball pitchers (9-14 years old)[126] These estimates indicate that injuries and pain are prevalent even among young participants. In fact, severe injuries requiring surgery are becoming more prevalent among young competitive baseball pitchers. The American Sports Medicine Institute reported that the number of the surgical cases performed on high school and collegiate baseball pitchers increased by 6-fold and 4-fold, respectively, between 1994-2000 and 2000-2004 periods.[154]

Another concern with baseball injuries is the high proportion of injuries that result in surgery and/or prolonged time loss from sport. It has been reported that 73% of all baseball injuries result in 7 or more days lost from sport, and that 25% result in more than 21 days lost.[133] The average days lost from participation after an injury is 7.6 days when excluding the cases requiring surgery, and 24.3 days when including surgical cases.[133] A prospective study by Krajnik et al[108] reported that approximately 10% of all shoulder injuries sustained by high school baseball players resulted in surgery. Once a baseball player undergoes a surgery, a prolonged time loss is expected. For example, a recovery time from ulnar collateral ligament reconstruction, which is one of the most commonly performed surgeries on baseball players,[157] ranges from 12 to 18 months.[79, 161, 194]

The injuries sustained during baseball also have consequences outside of sports. It has been estimated that each injury sustained by high school baseball players results in on average $466 of medical costs, $1454 of human capital cost, and $7385 of comprehensive cost.[107] The human capital cost was estimated from the probability of work loss, days lost if injury occurred, and average value of a day's work for the injured athlete and his family

members. The comprehensive cost took into account the human capital cost and the reduced quality of life. In addition to the economical cost, a study by Register-Mihalik et al[171] reported that some shoulder and elbow pain in high school pitchers result in difficulties performing tasks at home and at school, thus affecting their quality of life. These studies demonstrate that pitching-related upper extremity injuries not only result in time lost from sports, but also has economical and quality of life consequences.

### *2.2.2 Etiology*

The development of upper extremity injuries in baseball pitchers has been linked to joint loading during pitching. Based on the review of literature, common throwing-related injuries to the shoulder include pathologies to the rotator cuff muscles (i.e. tendinopathy, subacromial impingement, and posterior impingement) and biceps-labral complex. At the elbow, common injuries include injuries to the ulnar collateral ligament, flexor-pronator mass, ulnar nerve, and osseous structures. This section of the literature review will discuss how the pitching biomechanics relates to these injuries.

The rotator cuff is a group of muscles comprised of supraspinatus, infraspinatus, subscapularis and teres minor that originate on the scapula and insert onto the proximal humerus after encapsulating the humeral head. The muscles are strategically positioned to produce joint compression, and thereby provide joint stability throughout a wide range of shoulder movement.[118] The co-activation of the rotator cuff muscles limits an excessive humeral translation,[48, 81, 136] and thereby directs the line of action of the resultant muscle force through the glenoid fossa (effective glenoid arc).[113] Directing the resultant force to the area

within the effective glenoid arc allows the resultant muscle force to compress the joint and thereby provide joint stability.

The rotator cuff muscles that serve such important functions are susceptible to injuries during pitching due to the high magnitude of forces and moments experienced at the shoulder. These forces and moments results in a combination of tensile and compressive stresses within the rotator cuff muscles. It has been demonstrated using an animal model that the combination of the tensile loading and tissue compression results in greater tendon degeneration than tensile or compression loading alone.[185]

During pitching, the proximal force (internal force that resists distraction of the joint) at the shoulder reaches as high as 1-1.5 times the body mass.[50, 63, 69] This proximal force is associated with an increased tensile stress within the rotator cuff muscles, and thus gradual attenuation and failure (tendinopathy) of the muscles. Additionally, the force that pushes the humeral head superiorly is theorized to compress the supraspinatus tendon, long head of the biceps tendon, and subacromial bursa between the humeral head and the coracoacromial arch (subacromial impingement).[69, 134] The repetitive compression of the supraspinatus results in gradual fraying of the external surface of the tendon, where it abuts the anterior-inferior edge of the acromion process. This is problematic, since the area of fraying coincides with the "critical zone" of the supraspinatus, named for its poor blood-supply, and thus poor potential for tissue regeneration.[123, 124, 168]

The posterior rotator cuff muscles act to decelerate the arm after the ball release. Therefore, horizontal adduction moment and the force that acts to distract the joint would create a tensile stress within the muscles. In addition, the external rotation moment, combined with the extreme shoulder external rotation and horizontal abduction angles

achieved during the arm cocking phase can lead to impingement of the posterior rotator cuff muscles between the posterior glenoid rim and the posterior humeral head (internal or posterior impingement).[116, 143, 195] While the posterior impingement occurs naturally with humeral abduction and external rotation, the impingement becomes exaggerated and leads to a pathologic condition in baseball pitchers (pathologic internal impingement).[25, 27, 42, 58, 100, 143, 173, 190] Walch et al[195] arthroscopically evaluated the shoulders of 17 overhead athletes and found tears and fraying of the posterior rotator cuff tendon and labrum in 16 of the 17 athletes. The location of the fraying was precisely where the structures become impinged when the humerus is elevated and externally rotated.

In addition to the rotator cuff, glenoid labrum is another structure that is commonly injured in baseball pitchers. The glenoid labrum is a fibrocartilaginous ring that lines the outer margin of the glenoid fossa. The superior margin of the glenoid labrum, which serves as an anchor to the long head of the biceps tendon is commonly referred to as a biceps-labral complex.[56, 192] The bicep-labral complex is a common site of injury in overhead athletes.[28-31] In particular, an injury that results in tearing of the superior labrum in anterior to posterior direction (SLAP lesion) is a type of injury almost exclusively found in baseball pitchers and other overhead athletes. The SLAP lesion is theorized to occur as a result of the tensile stress that is placed on the superior labrum via the long head of the biceps.[21, 23, 29, 103, 111, 164, 184, 215]

The two instants during pitching when the labrum is susceptible to injury are 1) when the tensile loading on the biceps reaches its peak, and 2) when the shoulder reaches the maximum external rotation.[14, 111, 164, 215] The tensile loading of the long head of the biceps peaks during the acceleration and deceleration phases of pitching when the biceps resists rapid elbow extension and distraction forces at the shoulder and elbow joints.[111, 164, 215] It has

been demonstrated that the stress distribution on the superior labrum increase during a simulated deceleration phase of pitching.[164] During the arm-cocking phase of pitching, the maximal external rotation of the shoulder causes the line of pull of the long head of the biceps to shift posteriorly. When the long head of the biceps pulls on the glenoid labrum from a posterior direction, the tension from the tendon produces a sheer stress that "peels back" on the glenoid labrum ("peel back mechanism").[28, 29] While the tensile loading of the biceps is unremarkable during the arm-cocking phase, it has been demonstrated that the added sheer stress that "peels back" on the labrum can cause a tear under a lower tensile loading.[111]

The elbow joint also experiences high external loading during pitching. During the arm cocking and acceleration phases of pitching, elbow experiences a high magnitude of valgus moment accompanied by a rapid elbow extension, a type of loading commonly referred to as the valgus extension overload.[8, 50, 63, 69, 70, 178, 203] The valgus extension overload results in high tensile stress on the medial elbow structures, compressive stress on the lateral joint structures, and combination of compressive and sheer stress on the postero-lateral elbow, thus theorized to explain most of the pitching-related elbow injuries.[9, 13, 34, 43, 75, 122, 139, 160]

At the medial aspect of the elbow, the valgus loading results in development of high tensile stress within the ulnar collateral ligament complex, flexor pronator mass, and ulnar nerve. The ulnar collateral ligament complex consists of three bundles; anterior oblique, transverse, and posterior oblique. Of these bundles, the anterior portion of the anterior oblique bundle provides the greatest resistance against the valgus loading.[9, 12, 52, 75, 140, 141, 152, 169, 180] Since the anterior band of the anterior oblique ligament becomes increasingly taught

with elbow extension, the tensile stress experienced by the ligament is thought to increase during the acceleration phase, which explains why most injuries to the ulnar collateral ligament involve the anterior band of the anterior oblique ligament.[9, 12, 52, 75, 140, 141, 152, 169, 180] The elbow valgus loading experienced during pitching (64-120Nm)[63, 69, 159, 198] far exceeds the reported ultimate injury threshold of the ulnar collateral ligament (13.3-34Nm), which is considered the primary stabilizer of the joint.[10, 16] Because of the repetitive tension placed on the ligament, increased valgus laxity has been reported in collegiate and professional pitchers.[57, 182] In addition, adaptive thickening of the ulnar collateral ligament have been reported in high school pitchers who exhibit high elbow valgus loading during pitching.[97] It needs to be noted, however, that the ulnar collateral ligament is not the only structure responsible for resisting the valgus loading. Using cadavers, Morrey et al[139] reported that the ulnar collateral ligament is responsible for 31-54% of the resistance against the valgus moment provided by static structures (ligament, joint capsule, and osseous contact). In addition to the static structures, forearm flexor-pronator mass also produces significant varus moment to counteract the elbow valgus moment.[13, 122, 160, 181]

The flexor-pronator mass consists of four muscles that originate from the medial epicondyle of the humerus; pronator teres, flexor carpi radialis, flexor digitorum superficialis, and flexor carpi radialis.[13, 43, 122, 139, 160, 191] Several studies have investigated the contributions of the flexor pronator mass on medial joint stability by 1) observing the spatial relationship of the muscles,[43] 2) measuring valgus laxity while systematically loading the muscles,[122, 160, 191] and 3) estimating the force production of each muscle from the moment arm and physiological cross sectional area.[13] These studies agreed that the flexor carpi ulnaris, flexor digitorum superficialis, and pronator teres all make significant contributions to the dynamic

joint stability against the valgus moment.[13, 43, 122, 139, 160, 191] The tensile stress that develops in these muscles while resisting the valgus moment may exceed the physiological limit of the tissue and leads to elbow tendinopathy (i.e. medial epicondylitis).

While the ulnar nerve does not provide stability to the joint, injuries to the ulnar nerve often accompany injuries to the ulnar collateral ligament complex and the flexor pronator mass.[19, 197] This is because the compression and/or entrapment of the nerve within/underneath the anatomical structures (ex. medial intermuscular septum, cubital tunnel retinaculum, arcade of Struthers, and between the heads of the flexor carpi ulnaris muscle), can prohibit the smooth gliding of the nerve and thus increase the tension on the nerve.[86, 151, 197] Around the instant of maximal shoulder external rotation, the elbow is flexed to approximately 90 degrees. This position can further increase the tension and compression on the nerve, since the nerve forms a pulley at the cubital tunnel.[86, 151, 197] The repetitive tension placed on the nerve leads to an irritation and development of neuropathy, which may influence the activation/strength of the flexor pronator mass and causes sensory and/or motor impairment in the forearm.[86, 151, 197]

The valgus extension overload results in a compression and sheer stress on the lateral and postero-medial elbow structures.[9, 35] The lateral elbow where the capitellum and the radial head articulates, and the postero-medial elbow between the olecranon fossa and the trochlea, are the two locations where the high compressive and sheer stresses are experienced during the valgus extension overload, and thus are susceptible to injuries such as chondromalacia, osteochondral defect, and loose body found in the articular space.[9, 17, 22] A radiographic study has demonstrated a high prevalence of hypertrophy, separation, and fragmentation of the medial epicondyle in the group of Little League baseball players.[85]

Another study also demonstrated a high prevalence of osseous changes, including loose body and osteophyte formation on the radial head and posterior olecranon process in the professional baseball pitchers with and without the symptoms of elbow injury.[211]

It needs to be highlighted that the structures that are susceptible to injuries are also the key structures that provide stability to the shoulder and elbow joints. Therefore, an injury to one structure may lead to another, because the compromised joint stability may increase the loads placed on the other structures. The examples of this process are found at the shoulder and the elbow joints.[9, 16, 17, 36, 41, 48, 80, 81, 120, 121, 136] The weakness of the subscapularis muscle (one of the rotator cuff muscle) has been suggested to increase humeral external rotation and glenohumeral joint contact pressure, increasing the pitcher's susceptibility to posterior impingement and SLAP lesion.[136] The weakness/dysfunction of the rotator cuffs has also been linked to altered glenohumeral arthrokinematics, and thus increased risk of subacromial impingement.[36, 48, 80, 81] At the elbow, a resection of the olecranon after the osseous injury has been linked to increased tensile loading on the ulnar collateral ligament.[16, 17, 120, 121] Andrews et al[17] demonstrated that 25% of the baseball players who had a resection of the postero-medial osteophytes, proceeded to develop an elbow valgus instability and have reconstruction of the ulnar collateral ligament. On the other hand, insufficiency of the ulnar collateral ligament has been linked to decreased contact area and increased contact pressure between the postero-medial trochlea and olecranon during valgus loading.[9] Similarly, Conway et al[41] reported that more than 50% of the throwing athletes who underwent an ulnar collateral ligament reconstruction also presented with postero-medial osteophytes.

## 2.3 Pitching Biomechanics

Throwing is a fundamental motor skill that is acquired during childhood.[78] In the early stage, throwing is performed as an arm-dominated movement with minimal contributions from the lower extremity or trunk. With advancing developmental stage, individuals gradually incorporate trunk rotation, forward step, and horizontal arm adduction to acquire a mature movement pattern.[207] The acquisition of mature fundamental throwing movement forms a basis for the learning of the sports-specific skill; pitching. Pitching is typically learned in late childhood, and becomes refined during adolescence.[78] During adolescence, frequent use of the pitching skill in practice and game settings combined with rapid musculoskeletal growth result in rapid improvement in ball velocity,[78] gradual decrease in movement variability, and improved consistency of the aim.[78, 129] In addition, practice leads to development of a coordination pattern that is more economical (use less energy) and utilize multiple linked segment in a manner that produces optimal performance.[78, 129]

Biomechanics of pitching has been studied in numerous studies. Some of these studies simply provided general descriptions of the pitching technique,[7, 50, 53, 63, 65, 69-71, 159, 165, 166] while the others investigated the pitching kinematics parameters that are associated with injury,[11, 18, 32] joint loading,[7, 8, 44, 132, 178, 199, 201, 203, 206] and performance.[131, 187] The observations from these studies will be discussed in depth.

### *2.3.1 Description of the Pitching Biomechanics*

Pitching is traditionally described in six phases; 1) wind up, 2) stride, 3) arm cocking, 4) acceleration, 5) deceleration, and 6) follow through (**Figure 1**).[50, 159] At the beginning of each pitch, a pitcher stands facing a hitter with a ball held inside the glove. The wind up

phase starts when the pitcher takes a step back with the stride leg. As the pitcher takes a step back, the pitcher's body rotates 90°, so that lateral aspect of the leading (non-dominant side) shoulder faces the hitter. As the pitcher rotates the body, the knee on the stride leg is brought towards the chest, and the wind up phase ends when the knee reaches its maximum height.[50] This phase is a preparatory phase when the pitcher achieves a balanced position, from which to initiate the forward stride.[50]

When the runner is on base, the wind up phase becomes truncated in order to decrease the time available for the runner to steel the base.[54] Instead of pitching from a wind up, pitches are performed from the stretch. When pitching from the stretch the pitchers initiate the pitching motion with the trunk already positioned perpendicular to the pitching rubber.[54] The pitcher then quickly lifts the leg and transitions into the stride phase. While some believe that pitching from the stretch results in a "rushed" pitching movement, and thus altered kinematics and joint stress, it has been demonstrated that there are no clinically significant differences in kinetics, kinematics, and ball velocity between the pitches performed from a wind up vs. stretch.[54]

The stride phase starts when the knee starts to descend and ends when the stride foot contacts the ground at a distance approximately 85-100% of the pitcher's height (stride foot contact).[50, 71] During this phase that lasts 500-1000 milliseconds,[50, 63] a strong push-off force on the pitching rubber and the forward drive of the stride leg result in generation of the forward linear momentum towards the target.[128] In coordination with the lower extremity movement, the pitcher separates the ball from the glove and moves the arm down, back, and up into a semi-cocked position at stride foot contact.[50]

The instant of stride foot contact, which marks the beginning of the arm-cocking phase, is a pivotal instant in pitching when cessation of the forward movement of the lower extremity results in transfer of momentum to the upper body.[188, 206] As a result of the rapid forward rotation of the pelvis that starts before stride foot contact, the pitcher's pelvis is rotated 0-60 degrees towards the target at stride foot contact.[206] On the other hand, the upper torso remains closed at the instant of stride foot contact, which results in 1) temporal lag between the pelvis and upper torso rotation, and 2) angular separation between the pelvis and upper torso segments.[7, 8, 165, 166, 188, 206]

The temporal lag between the pelvis and upper torso rotations allows the pelvis to reach its peak angular velocity before the initiation of upper torso rotation, which is considered advantageous in maximizing the momentum transferred to the upper torso segment.[158, 165, 166] The summation of speed principle states that the speed of the distal segment in the linked system will be maximized if the movement of the distal segment started as the proximal segment reached its maximum speed.[165, 166] It has been reported that the angular separation between the pelvis-upper torso reach as high as 50-60° after stride foot contact.[94, 95] This angular separation results in an acute elongation of the internal and external oblique muscles, which maximizes the force produced by the muscles through utilization of the stretch shortening cycle and strain energy stored within the parallel elastic component of muscle fibers.[87, 188]

Optimizing the transfer of momentum and force production by the abdominal muscles result in peak velocity of the upper torso rotation (1200°/second) that is approximately twice the peak rotation velocity of the pelvis segment (620°/second).[71] The rapid upper torso rotation and forward translation of the upper torso result in linear acceleration of the

throwing shoulder (proximal end of the arm segment), which causes the arm and the forearm to lag behind the upper torso. The horizontal abduction angles during the arm-cocking phase reach 17° to 21°.[60, 71] In response to the lag, the pectoralis major muscle contracts to overcome the lag and move the shoulder into horizontal adduction.[98, 99] The combination of the forces resulting from the forward linear acceleration of the throwing shoulder and rapid shoulder horizontal adduction causes the forearm to lag behind the arm, and thereby force the shoulder into external rotation.[63] It has been reported that the pitchers' maximal shoulder external rotation angle reaches as high as 170-180°,[71] which is far beyond the passive shoulder external rotation range of motion attained during clinical examinations.[27, 135, 143] The shoulder internal rotation moment and elbow varus moment reach their peak immediately before the instant of maximal shoulder external rotation.[63, 70] Since these joint moments are directly related to the pitching-related upper extremity injuries, the instant of maximal shoulder external rotation is considered one of the instants with the highest potential for injury.[18, 69, 97]

The acceleration phase of pitching begins once the shoulder reaches the maximal external rotation. The acceleration phase that lasts approximately 36-38 milliseconds is characterized by a rapid shoulder internal rotation, elbow extension, and forward flexion and translation of the upper torso. These movements result in acceleration of the ball towards the target.[50, 159] During this phase, contraction of shoulder internal rotators (ex. latissimus dorsi and pectoralis major) along with the forward acceleration of the forearm produce rapid shoulder internal rotation velocity that reaches 6000-7000°/second.[63, 71, 73] In addition, the momentum produced by the rapid rotation of the upper torso results in production of a centrifugal force that leads to rapid elbow extension reaching as high as 2000°/second.[69, 71]

While the high activation level of the triceps has been reported during the acceleration phase,[98, 99] it has also been demonstrated that comparable elbow extension velocity can be achieved during this phase even after any contribution of the triceps muscle has been eliminated by introduction of a radial nerve block.[20] This observation indicates that the rapid elbow extension occurring during the acceleration phase of pitching is largely due to the momentum generated by the proximal segments.[20, 88, 89, 165, 166] The rapid shoulder internal rotation and elbow extension movement result in joint proximal forces at the shoulder and elbow joints that reach 1-1.5 times the body mass prior to ball release.[69, 71] The joint proximal forces, which resist the forces that act to distract the shoulder and elbow joints, have been linked to various pitching-related upper extremity injuries. Therefore, the instant of ball release is considered another instant of pitching that has high potential for injury.[69]

The deceleration phase starts once the ball is released from the pitcher's hand. During this phase, the shoulder continues to internally rotate until it reaches the maximum internal rotation. The shoulder decelerates from 7000°/second of internal rotation velocity to a complete stop within this phase that lasts approximately 50ms.[159] The deceleration is achieved by the eccentric work of the posterior shoulder muscles, biceps, and the trunk musculatures.[159] The deceleration phase is followed by the follow-through phase, during which the body catches up with the arm movement, and the pitcher gets into a fielding position.[159]

*2.3.2 Comparison of Pitching Techniques among the Pitchers of Various Levels*

Several studies have compared the pitching biomechanics among the pitchers of different levels.[7, 65, 71] One of these studies by Fleisig et al[71] reported that the youth, high

school, collegiate, and professional pitchers demonstrated remarkably similar pitching kinematics. On the other hand, the joint loading was significantly greater in older pitchers.[71] This is likely due to the greater body size (body mass and limb length) in older pitchers, since the kinetic variables were not normalized to the pitcher's mass or height.

The study by Aguinaldo et al[7] also compared the upper torso rotation kinematics and shoulder joint moments between youth, high school, collegiate, and professional pitchers. The main observation from the study was that the higher-level pitchers were able to delay the initiation of upper torso rotation compared to the younger pitchers (youth and high school pitchers), and were also able to perform pitches with a lower shoulder internal rotation moment (normalized to body mass and height) compared to the younger pitchers. In contrast to the finding from the study by Fleisig et al,[71] the professional pitchers in the study pitched with lower absolute (non-normalized) shoulder internal rotation moment compared to the collegiate and high school pitchers. This observation indicates that the ability to effectively use the trunk may be associated with an ability to pitch while placing a lower loads on the upper extremity joints.

Another study that compared pitching biomechanics among the pitchers of different levels focused on the within-pitcher variability of the pitching movement.[65] The study demonstrated that the joint kinematics were more variable in the younger pitchers. Specifically, the younger pitchers (youth and high school levels) demonstrated a greater variability in foot placement, knee flexion angle, pelvis angular velocity, elbow flexion angle, shoulder external rotation angle, and trunk forward tilt angle during pitching.[65] However, the average standard deviations for the knee flexion and elbow flexion angles in high school pitchers were only 3.2º±2.1º and 1.8º±0.8º, respectively. The standard deviation

of the temporal variables were only 1–3%, and there were no differences in the timing of events and the kinetics variables among the pitchers. In overall, the observations from this study indicate that the pitchers of all levels can pitch with a remarkable consistency.

*2.3.3 Pitching Kinematics, Joint Loading, and Injury*

Anecdotal evidence indicates that "poor" pitching technique can lead to pitching-related upper extremity injuries.[84, 94, 95, 126] However, only a few studies have directly linked the pitching kinematics to the pitching-related upper extremity injuries and/or pain. In 1978, Albright et al[11] investigated the association between the arm delivery and reports of shoulder and elbow symptoms at the end of the baseball season in youth and collegiate pitchers. The study reported that 73% of the pitchers who exhibited more horizontal arm delivery reported shoulder or elbow symptoms compared to 21% among the pitchers who exhibited more vertical arm delivery. Furthermore, the reported elbow symptoms were more severe in the pitchers with more horizontal delivery. The study was the first study to demonstrate the link between the pitching technique and the incidence and severity of the injury. However, in another study by Lyman et al[126] that investigated whether the quality of pitching technique was associated with the risk of shoulder and elbow pain in youth baseball pitchers, investigators did not demonstrate the relationship between the pitching technique and complaints of shoulder or elbow pain.

The inconsistencies in these study findings may be attributed to the fact that the development of pitching-related upper extremity injuries is multi-factorial.[68, 126, 127, 170] Other factors beside pitching technique, such as participation factors (ex. pitch count/innings[68, 126, 127, 170]) and physical characteristics (ex. humeral torsion[144, 205] and glenohumeral internal

rotation range of motion[5, 51]) have been linked to pitching-related upper extremity injuries. Therefore, studies investigating the link between the pitching kinematics/technique and injury, while taking the other contributing factors into consideration are needed in the future.

Currently, a small prospective study using 23 professional pitchers by Anz et al[18] is the only study that directly links the high joint loading and the pitching-related upper extremity injuries. The study demonstrated that the pitchers who sustained an elbow injury over the three baseball seasons, experienced a greater elbow varus and internal rotation moment at the baseline testing.[18] However, since this observation is based on a small sample of baseball pitchers, a larger prospective study is needed to investigate the effects of the pitching kinematics/technique on joint loading and injuries.

*2.3.4 Identification of Kinematic Parameters Associated with Joint Loading*

Despite the limited direct evidence linking the pitching technique and injuries, indirect evidences from the studies on upper extremity anatomy and pitching biomechanics support an idea that pitching kinematics is associated with the pitching-related upper extremity injuries. Therefore, several biomechanical studies have been conducted to identify the kinematic variables that are linked to greater joint loading at the shoulder and elbow joints. The common approach taken by these studies is to use regression models to identify the biomechanical predictors of joint loads that are linked to pitching-related upper extremity injuries.[7, 178, 199, 201, 203] Other studies have also used group comparisons and simulations to identify the factors that are linked to shoulder and elbow moments.[8, 132, 206] Based on the review of these studies, greater maximal shoulder external rotation angle and greater elbow extension angles at various time points[8, 178, 199, 201-203] have been repeatedly identified as

kinematic parameters that are associated with increased joint loading. Other kinematic variables that have also been linked to increased joint loading include shoulder abduction angle,[132, 203] trunk lateral tilt angle,[8, 132] timing of upper torso rotation,[8, 44] and pelvis orientation at stride foot contact.[206]

The maximum shoulder external rotation angle has been linked to greater shoulder proximal force[201] and elbow varus moment.[8, 178] Using a regression model that only included kinematic variables, Sabick et al[178] demonstrated that variance in the maximum shoulder external rotation angle accounted for 33% of the variance in the varus moment. This observation suggests that the greater external rotation angle during arm-cocking phase may be attributed to increased elbow varus moment and ultimately injury. The greater maximal shoulder external rotation angle has also been linked to greater shoulder proximal force.[199] Perhaps, a greater maximal shoulder external rotation angle results in a greater arc of motion for the upper extremity acceleration to take place before ball release, and thereby leads to a greater shoulder proximal force, and thus greater joint proximal forces.

The greater elbow extension angles at various time points have been linked to a greater shoulder proximal force and elbow varus moment.[8, 199, 201] During the arm-cocking phase, a centrifugal force that is produced from the rapid upper torso rotation acts to distract the shoulder joint and to extend the elbow. Perhaps, this is why the greater elbow extension angle and a greater shoulder distraction force are related to each other. Aguinaldo et al[8] discussed that the greater elbow extension angle results in a greater distance between the forearm mass and the longitudinal axis of the upper torso. This observation may explain why the greater elbow extension angle may be associated with the greater elbow varus moment.[8]

Greater shoulder abduction angle,[132, 203] greater trunk lateral tilt angle,[8, 132] early timing of upper torso rotation,[8, 44] and smaller pelvis orientation at stride foot contact[206] have also been linked to an increased joint loading. Using a simulation analysis, Mastuo et al[132] investigated the effects of shoulder abduction and lateral trunk tilt angles at ball release on elbow varus moment. The study demonstrated that shoulder abduction angle of 90-100° resulted in the lowest peak elbow varus moment. Werner et al[203] also identified that having a greater shoulder abduction angle at stride foot contact was predictive of a greater peak elbow varus moment. However, the un-standardized coefficient for the variable was 0.35, indicating a relatively small effect of the shoulder abduction angle on elbow varus moment. The simulation used in the study by Matsuo et al[132] also indicated that a greater lateral trunk tilt angle at ball release may be associated with a greater elbow varus moment when the shoulder abduction angle was greater than 110°. Similarly, Aguinaldo et al. reported a trend of association between the lateral trunk tilt angle at ball release and the peak elbow varus moment.[7]

The simulation analysis by Matsuo et al[132] demonstrated an interaction effect of the shoulder abduction and lateral trunk tilt angles on elbow varus moment. However, the regression analysis used in the same study failed to demonstrate the effects of shoulder abduction or lateral trunk tilt angles on elbow varus moment. The authors explained this discrepancy by speculating that the trunk tilt and shoulder abduction angles may be only one of many determinants of the elbow varus moment, and that other factors not examined in the study may have a greater influence on the varus moment. It is important to note, however, that the shoulder abduction and lateral trunk tilt angles in this study were measured at the instant of ball release. Since the elbow varus moment peaks around the instant of maximal

shoulder external rotation, the effects of these angles on elbow varus moment may need to be investigated at the instant of maximal shoulder external rotation.

Aguinaldo et al[8] and Wight et al[206] examined the effects of pelvis and upper torso rotation styles on the shoulder and elbow joint loading. Aguinaldo et al[8] compared elbow varus and shoulder internal rotation moments between the pitchers who initiated upper torso rotation before vs. after the stride foot contact. The investigators reported that the elbow varus moment was greater in the pitchers who started rotating their upper torso early, compared to the pitchers who delayed the upper torso rotation until after the stride foot contact. This observation suggests that the timing of upper torso rotation may be important in minimizing the elbow varus moment.

Wight et al[206] compared shoulder and elbow joint moments between the pitchers who demonstrated an open (>30 degrees) vs. closed (<30 degrees) pelvis orientations at the instant of stride foot contact. The investigators reported that the pitchers who demonstrated a closed pelvis experienced greater shoulder and elbow joint loads compared to the pitchers who demonstrated an open pelvis at stride foot contact. The lower joint loading in the pitchers with an open pelvis may be explained by the fact that these pitchers also demonstrated an earlier achievement of a peak pelvis angular velocity, which is associated with an efficient transfer of momentum to the upper body.[165, 166, 206] The pitchers with an open pelvis also demonstrated a shorter duration of the arm-cocking phase, which has been linked to a lower shoulder distraction force in collegiate pitchers.[201] Interestingly, the kinematics between the pitchers with open and closed pelvis at stride foot contact became remarkably similar by the end of the arm-cocking phase when the loads at the shoulder and elbow joints reached their peaks. This observation indicates that the pitching motion in the

early phases of pitching may influence the loads placed on the upper extremity joints during the late arm-cocking and acceleration phases.[206]

*2.3.5 Identification of Kinematic Parameters Associated with Performance*

A ball velocity is an outcome that is of great interest to baseball coaches. Several biomechanical studies have identified the biomechanical variables that are predictive of ball velocity.[128, 132, 187, 204] For example, greater peak ground reaction force during stride (push-off force)[128] and having more flexed knee at stride foot contact[204] have been linked to a greater ball velocity. Additionally, demonstrating a greater knee extension angle[204] and greater knee extension velocity at ball release[131] have been linked to greater ball velocity. These observations indicate the importance of the lower extremity movement in producing ball velocity.

At the upper body segments, greater elbow extension velocity, upper torso rotation velocity, greater elbow flexion angle[204] and shoulder horizontal abduction angle[187] at stride foot contact, greater maximal shoulder external rotation angle,[131, 204] and forward trunk tilt angle at ball release[131, 187, 204] have been identified as predictors of higher ball velocity. In pitching, which is characterized by the proximal-to-distal segment rotations, the velocity of the distal segment (hand/ball) is a direct result of the sum of the velocities of the proximal segments. Therefore, it is not surprising that the elbow extension and upper torso rotation velocities are associated with greater ball speed. In addition, some of the temporal variables, such as a shorter time from stride foot contact to maximal shoulder external rotation, and a greater time to maximal shoulder horizontal adduction, have been linked to higher ball velocity.[187, 204] This observation indicates that the timing of the critical events may also play

a role in producing ball velocity. In terms of joint kinetics, peak elbow extension moment and shoulder/elbow joint proximal forces have been associated with higher ball velocity.[187]

It needs to be noted here that some of the biomechanical variables that are associated with increased ball speed are also associated with an increased joint loading, which may suggest that high joint loadings may be unavoidable when the goal of the skill is to produce high ball speed. For example, the greater maximal shoulder external rotation angle during pitching and higher proximal forces at the shoulder and elbow joints have been linked to higher ball velocity,[8, 178] but are also identified as potential predictors of the shoulder and elbow joint moments.[187, 204] Furthermore, in a small scale (n=23) prospective study, Bushnell et al[32] demonstrated that the pitchers with higher pitch velocity may be more susceptible to sustaining an elbow injury.

On the other hand, in a study by Wight et al,[206] which compared biomechanical variables between the pitchers with two types of pelvis rotation styles, the pitchers who demonstrated more closed pelvis orientation at stride foot contact experienced a higher joint loading compared to the pitchers who demonstrated an open pelvis orientation, yet the ball velocity was not significantly different between the groups. Additionally, in the previously mentioned study by Aguinaldo et al,[7] the professional pitchers who presumably pitched faster (ball speed was not reported in the study) compared to the high school and collegiate pitchers experienced lower absolute and normalized shoulder external rotation moments compared to the high school and collegiate pitchers. These studies suggest that production of higher ball velocity may not necessarily incur high joint loading. However, more studies are needed to determine if there is a trade off between the performance (ball velocity) and the joint loading.

*2.3.6 Identification of the Technical Errors Associated with Joint Loading and Performance*

As discussed above, various kinematic, temporal, and kinetic variables have been identified as potential predictors of joint loading and performance. While these findings are meaningful in advancing the understanding of pitching biomechanics, a limitation of these studies is that the kinematic variables identified in these studies cannot be detected without the use of advanced motion capture systems. Since such motion capture systems are rarely available outside of the laboratory-setting, it is difficult to translate the observations from these studies to clinical applications.[44]

Recognizing this limitation, Davis et al[44] took a different approach and investigated the effects of the common technical errors on joint loading. The technical errors examined in their study were commonly demonstrated among the youth and adolescent pitchers and were easily identifiable by the baseball coaches and parents. The specific technical errors examine in the study were: 1) leading with the hips, 2) hand-on-top position , 3) arm in throwing position, 4) closed-shoulder position, and 5) stride foot toward home plate. The investigators observed that the pitchers who failed to demonstrate closed-shoulder at stride foot contact and hand-on-top position during the stride phase experienced greater elbow varus and shoulder internal rotation moments compared to the pitchers who performed those parameters correctly.[44] This observation is clinically meaningful in that baseball coaches, parents, or sports medicine clinicians can use this information to identify pitchers who may be at a higher risk of injury. Providing instruction to correct the technical errors in these pitchers may possibly lead to prevention of the pitching-related upper extremity injuries.

Therefore, more studies are need to identify observable technical errors that are associated with increased joint loading.

The technical errors can be defined as specific movement patterns observed during pitching that are considered to limit the pitcher's performance and/or increase the loads placed on the pitcher's joints. These technical errors are typically, based on an empirical evidence gathered by a number of baseball coaches.[94, 95] While there are many technical errors that coaches look for when evaluating a pitching technique, experienced pitching coaches recommend addressing technical errors of the trunk before the others, because a proper movement of the trunk is considered a prerequisite for the proper upper extremity movement .[94, 95] This notion is supported by the fact that the trunk is a proximal base for the upper extremity segments, and thus kinematics of the trunk segment has a direct influence on the upper extremity kinematics and kinetics.[7, 8, 89, 158, 165, 166]

Based on the review of the books written by the experienced pitching coaches, and interviewing several high school and collegiate pitching coaches, we have identified five observable technical errors of the trunk that are generally considered to be associated with poor performance and/or increased joint loading.[94, 95] These technical errors include: 1) open shoulder (OS), 2) backward lean at stride foot contact (BLSFC), 3) lateral lean at stride foot contact (LLSFC), 4) lateral lean at maximal shoulder external rotation (LLMER), and 5) inadequate forward flexion at ball release (FT).

The open shoulder (OS) is a technical error characterized by a premature upper torso rotation, resulting in the anterior aspect of the leading shoulder facing the target at stride foot contact.[7, 8, 44, 94, 95] This error was present in 15% of the 45 pitchers who participated in our pilot test. Correctly, the pitchers' shoulders should remain closed until after the stride foot

contact to create a temporal lag and angular separation between the pelvis and upper torso segments.[165, 166, 188] This error can be identified from the anterior view, by observing the anterior aspect of the leading shoulder. The error is present if the anterior aspect of the leading shoulder is visible at stride foot contact. This technical error was previously linked to an increased elbow varus moment in the study by Davis et al.[44] The authors discussed that OS leads to "hyper-angulation" or excessive horizontal abduction of shoulder, which is though to increases the stress on the anterior shoulder structures, and thus lead to shoulder pain and injury. However, the horizontal abduction angle was not reported in the study. In addition, OS may be associated with an ineffective use of trunk, since it is characterized by a premature initiation of upper torso rotation.[7, 8] It has been theorized that the ineffective use of trunk can lead to a greater reliance on the distal joints (shoulder and elbow) to generate momentum, and thus increased loading on the upper extremity joints.[7, 8] Aguinaldo et al[7] demonstrated that the high school pitchers who initiated the upper torso rotation earlier than the collegiate and professional pitchers, and thus were less effective in utilizing the trunk, pitched with higher peak shoulder internal rotation moment compared to the collegiate and high school pitchers who initiated the rotation later.

Backward trunk lean at stride foot contact (BLSFC) is characterized by a pitcher's trunk that is leaned posteriorly, resulting in a failure to maintain the head directly over the stride foot ankle at the instant of stride foot contact.[94, 95] This error was present in 49% of the pitchers in our pilot testing. Correctly, the pitchers' head and upper torso should be vertically aligned over the stride foot ankle at the instant of stride foot contact.[94, 95] The error can be identified from the anterior view, by observing the position of the pitcher's head relative to

the vertical line passing through the stride foot (ankle). The error is present if the head is positioned posterior to the vertical line.

Similarly, lateral trunk lean at stride foot contact (LLSFC) is characterized by a pitcher's trunk that is leaned laterally towards the stance leg, resulting in a failure to maintain the head directly over the umbilicus.[94, 95] This error was present in 29% of the pitchers in our pilot testing. Correctly, the pitcher's head and upper torso should be vertically aligned over the umbilicus at stride foot contact.[94, 95] The error can be identified from the sagittal view, by observing the position of the pitcher's head relative to the vertical line passing through the pitcher's umbilicus. The error is present if the pitcher's head is positioned behind the vertical line.

The magnitude of joint loading is unremarkable at the instant of stride foot contact. However, the instant of the stride foot contact is a time point that precedes the arm-cocking and acceleration phases of pitching.[188, 206] Therefore, BLSFC, LLSFC, and OS can influence the upper torso kinematics, and thereby affect the upper extremity kinematics and kinetics during the arm-cocking and acceleration phases of pitching.[94, 95]

Lateral trunk lean at maximal shoulder external rotation (LLMER) is characterized by a pitcher's trunk that is leaned laterally towards the non-throwing arm at the instant of maximal shoulder external rotation and a failure to maintain the head directly over the stride foot (ankle).[94, 95] This error was present in 67% of the pitchers in our pilot test. Correctly, the pitchers head should remain vertically aligned with the stride foot so that the center of mass is maintained over the base of support.[94, 95] While some degree of lateral trunk tilt may be permissible at the instant of maximal shoulder external rotation, a gross lateral deviation of the head is considered a technical error. The error can be identified from the frontal view, by

observing the position of the pitcher's head relative to the vertical line passing through the stride foot (ankle). The error is present when the pitcher's head is positioned at least a head-width away from the vertical line.

The instant of maximal shoulder rotation marks the end of the arm-cocking phase and the beginning of the acceleration phase. The lateral tilt of the trunk during the arm-cocking phase results in production of shoulder adduction moment that is counteracted by the shoulder abduction moment produced by the deltoid muscles. Along with the horizontal adduction moment produced by the pectoralis major muscle, this shoulder abduction moment is considered as one of the main factors that generate the shoulder internal rotation and the elbow varus moment during the arm-cocking phase. In addition, the lateral deviation of the head during the acceleration phase of pitching may result in acceleration of the upper torso and arm towards the non-throwing shoulder, which may cause the forearm/hand to move away from the midline of the body, and as a result increase the elbow extension angle. As discussed previously, a greater elbow extension angle during the acceleration phase of pitching has been linked to an increased elbow varus moment and shoulder proximal force.[8, 199, 201, 203] The lateral shift of the head and upper torso may also direct the linear momentum of the upper body away from the direction of throw, thus affect ball speed and accuracy.

Inadequate forward flexion at ball release (FT) is characterized by a pitcher's failure to adequately tilt the trunk forward at ball release. This error was present in 22.7% of the pitchers in our pilot testing. Correctly, the pitchers' forward trunk tilt angle should be approximately 30° from vertical at the instant of ball release.[94, 95, 147] The error can be identified from the sagittal view, by observing the forward trunk tilt angle. In this study, the pitcher will be considered to have this error, if the forward trunk tilt angle appears to be less

than 20° from vertical. A greater forward tilt angle has been linked to a greater ball velocity.[131, 187, 204] Therefore, inadequate forward trunk tilt at ball release may lead to decreased ball velocity.

In addition to the potential effects of the technical errors on joint loading and performance, the technical errors at the trunk may be related to quality of pitching technique, since the proper trunk movement is considered a foundation for the proper upper extremity movement.[94, 95] The technical errors of the trunk described above can be identified using video cameras. Therefore, investigating the association between these technical errors and joint loading, performance, and quality of pitching technique may provide information that baseball coaches, parents, and sports medicine clinicians can utilize to identify pitchers who may be able to improve performance or may be at a higher risk of injury. Identification of such pitchers may lead to performance enhancement and/or prevention of pitching-related upper extremity injuries.

## 2.4 Methodological Considerations

In this section of the literature review, considerations that has lead to selection of the specific study methodology will be discussed. Specifically, considerations that lead to selection/designing of the instrumentation, data collection procedure, and data reduction procedures will be discussed.

### *2.4.1 Instrumentation*

The pitching distance and mound specification is regulated by the high school, collegiate, and professional baseball organizations. The standard pitching distance set by these organizations is 18.44m (60 feet 6 inches).[1, 2, 4] These regulations also specify that the

pitching mound should be 25.4cm (10 inches) in height and 5.5m (18 feet) in diameter.[1, 2, 4] In order to assess the pitcher's technique, it is important to conduct testing in an environment that is similar to the outdoor baseball field. Therefore, an artificial indoor pitching mound that meets the regulation height and slope was constructed, and the pitches will be performed into a backstop that will be placed at a regulation distance away from the pitching rubber.

The biomechanical data during the pitching trials will be captured using a seven-camera motion analysis system (Model: MX-40, Vicon Systems, Centennial, CO) and two force plates (Models: 4060-10/4060-NC, Bertec Corporation, Columbus, OH). In previous studies, pitching kinematics have been commonly captured at a sampling rate of 200[50, 61, 67, 69, 132, 200, 201, 204] or 240[8, 54, 55, 65, 74, 93, 132] frames per second, yet a sampling frequency that is as high as 500Hz have been used in recent studies.[97, 146] While there are many studies that investigated the pitching kinematics, only one study has examined the ground reaction forces during pitching. In this particular study, the ground reaction forces were sampled at 1000 Hz.[128] When synchronizing the kinematic and the kinetic data, the frame rate for the kinetics should be a multiple of the frame rate of the kinematic data. Therefore, the kinematic data will be sampled at 300 Hz and the force plate data will be sampled at 900Hz in this study.

### *2.4.2 Testing Procedure*

Prior to performing pitches, most studies allow unlimited time for the participants to perform stretching, jogging, and warm-up throws as they normally do on a game day.[7, 8, 53-55, 59-61, 65, 69, 72, 74, 97, 101, 132, 146, 148, 200, 206] This is critical in minimizing the potential risk of injury and ensuring that the pitchers become comfortable with pitching in an environment that is different from the outdoor pitching mound. Similarly, pitchers are encouraged to perform

several warm up pitches after the reflective marker are placed on their body, so that they become accustomed to pitching with the markers attached to their body.

The number of pitches performed by the pitchers varied across studies. In studies that captured the pitching kinematics during a fast pitch, participants performed 2-3 pitches,[63, 137] 5-20 pitches,[7, 8, 53, 59, 65, 67, 69, 71, 72, 91, 102, 132, 146, 149] until they made 3-5 strike pitches,[128, 206] or until they fulfilled 10 representative pitches, excluding the wild pitches that missed the target.[200, 201, 204] In studies that compared the different types of pitches or the pitches performed under different conditions (ex. stretch vs. wind-up), pitchers performed 5-10 pitches per pitch type/condition.[54, 55, 61, 74, 148] While most studies selected 3-5 fastest strike pitches and used the averages of the trials for statistical analyses,[50, 53, 54, 59-61, 65, 67, 69, 71, 74, 132, 146] some studies used a single pitch with the highest self-rating,[7, 8] or an average of 10 trials.[97, 159]

When developing a testing protocol, investigators need to capture enough number of trials so that the kinematics that are representative of the pitcher's technique can be calculated from the trial averages. Previous studies demonstrating a small variability in the kinematic parameters, suggests that only a small number of pitches may be needed to capture the representative technique. Another consideration when developing a testing protocol is the impact of study participation on pitchers' practice/game schedule. The 2010 Position Statement for Youth Pitchers from the American Sports Medicine Institute recommends that 7-18 year old pitchers take 1-day rest after performing 21-35 pitches, and 2-day rest after performing 36-50 pitches.[6] It is ideal that the number of pitches performed by the pitchers is kept under 21, so that the data collection causes no interference with the pitchers' training/practice schedule.

*2.4.3 Data Reduction Procedure*

When using an automatic motion capture system, three-dimensional coordinates of the reflective markers are calculated within the software. The three-dimensional coordinates exported from the software will be first filtered to minimize the noise in the signal. While the variety of digital filters has been used previously, most studies used a dual pass (zero-shift) 4th order Butterworth filter with a cutoff frequency ranging from 10-18Hz.[53-55, 59-61, 65, 67, 69, 71, 74, 132, 137, 148, 149, 200, 201, 204] Fleisig et al[67] recommended the use of 13.4Hz cut off frequency based on the method described by Winter et al.[210] This cut off frequency has been used in many studies that adopted this recommendation.[53-55, 60, 61, 65, 67, 69, 71, 74, 132] We would have adopted this recommendation, if the data in our study were to be collected at 200 frames per second. However, the kinematic data our study will be collected at 300 frames per second, and therefore the optimal cutoff frequency for the data will be determined using an equation described by Yu and Hay.[216]

Based on the filtered three-dimensional coordinate data, the locations of the joint centers need to be estimated. There are several ways, in which the locations of the shoulder and elbow joint centers have been defined in the literature. Fleisig et al[67] manually digitized the surface markers and the shoulder/elbow joint centers during pitching trials and developed equations that estimate the location of the shoulder and elbow joint centers from the surface markers. The equations have been used in many studies conducted by Fleisig and colleagues.[37, 53-55, 59-62, 65, 71, 72] Similarly, Veeger et al[193] developed a regression model that estimates the location of the shoulder joint center based on the markers placed on the scapula. While several investigators have used this method to estimate the location of the shoulder

joint center,[7, 8, 137] the subcutaneous movement of the scapula during a dynamic task is a concern.

Wight et al[206] calculated the location of the shoulder joint center based on an estimation method described by Rab et al.[167] The method estimates the location of the shoulder joint center at a point 17% of the length of the humerus from the acromion marker in the direction of the negative trunk longitudinal axis. Rab et al[167] examined the stability of the calculated shoulder angles when the marker location was moved by 1cm, and demonstrated that the variation in the marker placement resulted in less than 5º variations in the shoulder angles. Since no such data have been reported for the method described by Fleisig et al,[67] the method described by Rab et al[167] will be used in this study. Since the participants in the study by Wight et al[206] was relatively homogeneous in body size, the investigators estimated the location of the shoulder joint center as a point that was 5cm from the acromion marker for all participants. In our study, the estimation of the location of the shoulder joint center will be individualized, since our subjects (high school pitchers) will likely vary in height.

Many studies has used the equation developed by Fleisig et al[67] to estimate the location of the elbow joint center.[37, 53-55, 59-62, 65, 67, 69, 71, 72, 74, 200, 201, 204] This method estimates the location of the elbow joint center based on the length of the radius and the locations of the markers on the wrist, lateral elbow, and hand. This estimation method was likely used because the motion capture system used by Fleisig et al did not have a high enough resolution to track both medial and lateral elbow markers.[50] When the resolution of the motion capture system allows capturing of the medial and lateral elbow markers, the location of the elbow joint center can be simply estimated as the mid-point between the medial and

the lateral elbow epicondyle markers, as has been done in studies by Wight et al[206] and Nissen et al.[148, 149]

In analysis of pitching biomechanics, body is modeled as a linked segment model with trunk (pelvis and upper torso), arm, forearm, hand, and ball. While there are various ways to define these segments, these segments will be defined in accordance with the recommendation by the International Society of Biomechanics (ISB) in this study.[212, 213] The goal of the ISB recommendation is to encourage researchers to use a standard definitions of segment/joint coordinate systems and descriptions of joint angles to facilitate comparisons of the obeservations from different studies.[212, 213] It is important that investigators start following the ISB recommendation.

Two common method to calculate joint angles are projection angle method and the Euler angle method. Conventionally, many studies have used the projection angle method described by Feltner and Dapena[63] to calculate shoulder joint angles. However, the limitation of this method is that it results in inaccurate angle calculations when the movements are out of plane. During pitching, a significant amount of movement occurs in all three planes of motion, and therefore the projection angle may not be appropriate. Similarly, trunk kinematics during pitching have been commonly described using a projection angle method.

In this study, the joint angles will be calculated using the Euler angle method. The Euler angle method expresses the angles between the segments as a sequence of three rotations. The advantage to this method is that Euler angles are anatomically relevant, and thus readily interpretable by clinicians/coaches. The limitation of this method, on the other hand, is that the calculated angles are subjected to a singularity problem, and that the angles

are dependent on the order of rotation. For this reason, Euler angle sequence recommended by the ISB will be used in this study.[212, 213]

The kinematic variables during pitching are commonly reported at critical time points. The critical time points during pitching are instants of stride foot contact, maximal external rotation, and ball release.[7, 8, 50, 69, 159] In previous studies, the timing of stride foot contact was identified as an instant when the velocity of the lead ankle marker decreased to less than 1.5m/s.[37, 50, 53-55, 59-62, 65, 67, 71, 159] In the current study, stride foot contact will be determined as the instant when the vertical ground reaction force from the stride foot exceeded 10N, because the force plate data will be collected along with the kinematic data.[150] The instant of maximal shoulder external rotation will be determined from the calculated joint angle data.

In studies that utilized manual digitization method or used video cameras that are synchronized with the automatic motion capture systems, the instant of ball release was defined as the first frame when the ball separated from the hand.[101, 142, 146, 159] In studies that utilized automatic motion capture system with no videos, the timing of ball release needs to be determined from the other sources of data. Escamilla and colleagues[37, 53-55, 59, 61, 65, 67, 71, 74] defined the instant of ball release as the 2nd frame after the wrist marker surpassed the elbow marker in the direction of throw (global X-axis). Alternatively, Werner et al[200, 201, 204] determined ball release as a frame after the peak resultant linear velocity of the marker on the 3rd metacarpal head was reached. Wight et al[206] and Nissen et al[148, 149] placed reflective markers/tape on the ball and determined ball release as an instant when the distance between the markers on the hand and ball exceeded the specified threshold. The method used by Wight et al[206] and Nissen et al[148, 149] seemed reasonable. However, in our pilot testing, we

experienced difficulty capturing the reflective tape on the ball since the pitcher's grip often blocked the line of sight of the tape. Therefore, the method similar to what described by Escamilla et al[61] will be used to determine the instant of ball release. Kinematic data in our study will be captured at a higher rate (300 frames per second) than the data captured by Escamilla et al (200 frames per second).[61] Therefore, we will determine the average timing (frame #) of ball release relative to the frame when the wrist surpass the elbow in a direction of throw, using the high-speed (300 frames per second) video from the first 15 pitchers.

When calculating joint kinetics, inertial characteristics of the body segment need to be estimated from the anthropometric measures. Specifically, segment mass, location of the segment center of mass (COM), and radius of gyration about the segment COM need to be estimated in order to calculate joint forces and moments. While various estimation equations are available,[38, 47, 162] the method developed by Clauser et al[38] will be used in this study to estimate the segment mass and the location of the segment COM. This is because the estimation equations by Clauser et al[38] take body mass, segment length, breadth, and circumference into account, instead of body mass alone. The radius of gyration of the arm and forearm segments will be estimated from the method described by Dempster et al.[47]

Based on the kinematic data and the inertial characteristics of the body segments, inverse dynamics will be used to calculate joint reaction forces and moments experienced at the shoulder and elbow joints.[63, 209, 217] The inverse dynamics is based on the Newton's second law, which states that the sum of all forces/moments acting on the segment is proportional to the linear/angular acceleration of the segment. The joint reaction forces will be calculated based on the segment mass, location of the COM, linear acceleration of the segment COM, and the joint reaction forces on the distal end of the segment. The joint

moment will be calculated from the segment moment of inertia, joint reaction forces at proximal and distal end of the segments, moments at the distal end of the segment, and angular velocity and acceleration of the segment about the segment COM.

While many of the earlier studies reported raw (non-normalized) kinetic data,[8, 53-55, 60, 63, 72, 74, 101, 102, 176-178] more and more studies are reporting normalized kinetic values. Specifically, most studies normalize joint forces to participant's body weight (=body mass*9.81), and normalize joint moments to a product of participant's body weight and height to account for the differences in segment mass and length between participants. In a recent study, normalized joint kinetics were further normalized to ball velocity to express the "efficiency" of producing ball velocity.[44]

*2.4.4 Quality of the pitching mechanics*

A quality of movement is often assessed using a checklist of technical points that are critical or relevant to the skill.[77, 125, 126, 147, 214] The raters observe the movement in real time or review the video recordings to analyze each technical parameters. The American Sports Medicine Institute developed a 24-item pitching evaluation tool based on their database of kinematic data.[126, 147] While it has been reported that only 4 out of the 24 parameters demonstrate good validity (Kappa > 0.41) against the rating based on data captured using a motion analysis system, it has also been reported that 22 out of the 24 parameters have good (Kappa >0.41) intra-rater agreements.[147] This form is the only qualitative analysis protocol currently available that allows systematic evaluation of the pitching technique without the use of laboratory-based motion analysis system.

*2.4.5 Ball speed and Accuracy*

Ball speed is typically calculated as the average of pitches included in the analysis.[18, 32, 54, 59-61, 65, 66, 71, 74, 131, 178, 199, 201, 203, 206] However, there is no "typical" method to quantify the accuracy of pitches, because there are very few studies that evaluated pitch accuracy. In a small number of studies that looked at pitch accuracy, accuracy was quantified as the total number of strike pitches,[179] or calculated as an average distance of the ball from the intended target, using the recording from a high-speed camera.[130] In order to quantify accuracy of the aim with higher precision, accuracy of the pitch will be calculated as the average distance between the "X" marked at the center of the strike zone and the location where the ball hit the target.

# CHAPTER III

# METHODS

## 3.1 Study Design

The purpose of the study was to determine the effects of the technical errors of the trunk on pitching joint loading, performance, and quality of pitching technique in high school baseball pitchers. We addressed this question through comparisons of the joint loading, performance measures, and quality of pitching technique (1) between the pitchers with and without each technical error (open shoulder (OS), lateral lean at stride foot contact (LLSFC), backward lean at stride foot contact (BLSFC), lateral lean at maximal shoulder external rotation (LLMER), and inadequate forward trunk tilt at ball release (FT)), and (2) between the pitchers who demonstrated 0, 1, 2, and 3 technical errors. In addition, we conducted several secondary analyses to supplement the observations from these comparisons.

## 3.2 Participants

An a-priori power analysis for the primary variables of interest (kinetic variables normalized to body mass and height)[67] indicated that in order to detect a 10% difference in the variables between the pitchers with and without the technical errors with a statistical power of 80% with a type I error rate that is no greater than 0.05, a minimum of 17 participants are needed in each comparison group. It was expected that the prevalence of the

technical errors at the critical time points would vary. However, we did not have any control over the errors demonstrated by each pitcher.

The pitchers were recruited from the local high schools and summer/fall baseball leagues in the communities surrounding the university. The pitchers between the ages of 13-19 years, who have pitched in at least two baseball seasons as a starter or a relief were included in the study. The pitchers with any on-going injury/pain/muscle soreness that keeps them from pitching as they normally would were excluded from the study. Underarm (submarine) or sidearm pitchers were also excluded from the study. Prior to participation, participants and one of their parents read and signed the informed consent forms approved by the University of North Carolina at Chapel Hill Biomedical Institutional Review Board.

### 3.3 Instrumentation

A custom-built pitching mound was constructed to meet the high school, collegiate, and professional baseball regulations (**Figure 7**).[1-4, 59, 132, 187, 204] The mound consisted of a top flat portion (Dimensions: 0.25m H x 1.68m W x 0.69m L) and a slope (Dimensions: 0.25m H x 1.68m W x 2.51m L, Inclination: 4°). From the pitching mound, the pitches were performed pitched into a backstop (Athletic Training Equipment Company, Sparks, Nevada) (Dimensions: 1.52m H X 1.32m W) with a rectangular strike zone (Dimensions: 0.64m H X 0.38m W) placed at a distance of 18.4 m (60’6”: regulation pitching distance) from the pitching rubber (**Figure 8**).

**Figure 7**. Custom-built indoor pitching mound


**Figure 8**. Backstop with "X" marked as a target

The pitching "rubber" was fabricated using an aluminum plate (0.415m W x 0.125m L x 0.015m H), and was fitted to a force plate (Model: 4060-10, Bertec Corporation,

Columbus, OH) that was instrumented on the flat portion of the mound (**Figure 3**). The data collected from this force plate were not used for analyses in this study. The second force plate (Model: 4060-NC, Bertec Corporation, Columbus, OH) that was instrumented on the slope, captured the ground reaction forces from the stride foot, which was used to determine the instant of stride foot contact. The position of this force plate was adjusted to accommodate the pitchers with different stride lengths. The ground reaction forces from the force plates were captured at 900Hz, and were synchronized with the kinematic data within the data collection software.

The kinematic data were captured using a seven-camera motion analysis system (Model: MX-40, Vicon Systems, Centennial, CO) with Vicon Nexus automatic digitization software (Version 1.6) (Vicon Systems, Centennial, CO) (**Figure 9**). The system was calibrated for a volume of 2m H x 2m W x 3m L before the testing sessions. The kinematic data were captured at 300 frames per second. The origin of the global reference frame was set at the right anterior corner of the pitching rubber (**Figure 9**). The positive X-axis was aligned to the direction of the throw, positive Y-axis was directed to the pitcher's left when facing the direction of throw, and positive Z-axis was directed superiorly (**Figure 9**).

Two high-speed video cameras (Model: Exilim FX-1, Casio Computer Co., Ltd., Tokyo, Japan) were used to capture the frontal and sagittal views of the pitching technique. The frontal view camera was placed 3m in front of the anterior edge of the pitching mound at a height of .20m from the floor. The sagittal view camera was placed on the right side of the pitcher, perpendicular to the direction of throw at a distance of .75m in front of the pitching rubber. The location of the sagittal view camera was selected as approximately 50% of the average stride length from the pitching rubber, calculated based on the data from a previous

study (Average stride length = 85% of pitcher's height, 0.85*Average height (1.83m) = 1.56m).[71] We attempted to place the camera on the left side of the pitcher for the left-handed pitchers. However, the distance between the mound and the wall on the left side of the laboratory was not sufficient to capture the pitching movement from the left side (camera was too close to the pitcher). The grids on the camera monitors were aligned to the horizontal and vertical lines on the laboratory walls to ensure that the videos captured were properly aligned horizontally and vertically. The video were captured at 300 frames per second. The two cameras were connected to and controlled by the separate laptop computers so that the videos can be directly stored onto the computer hard drive for immediate processing and viewing.

An additional high-speed video camera (Model: Exilim FX-1, Casio Computer Co., Ltd., Tokyo, Japan) was placed approximately 12m in front of the backstop to record the location of the ball as it hit the backstop (ball strike). For each pitch, the frame immediately before the ball strike was identified and exported as an image file for a calculation of pitch accuracy. The videos were captured at 300 frames per second. A radar gun (Sports Radar Ltd., Homosassa, FL, Model: SR3600) was used to capture a ball speed. The radar gun was positioned 3m behind the pitcher and was positioned so that the aim of the gun was aligned with the trajectory of the ball after the ball release. The position and the aim of the radar gun was adjusted for each pitcher for an optimal alignment. Based on our pilot testing using 18 pitches from 10 pitchers, the average absolute error between the ball speed measured using a radar gun and the ball speed calculated from manual digitization of the ball after release was 1.65 km per hour (1.0 mile per hour).

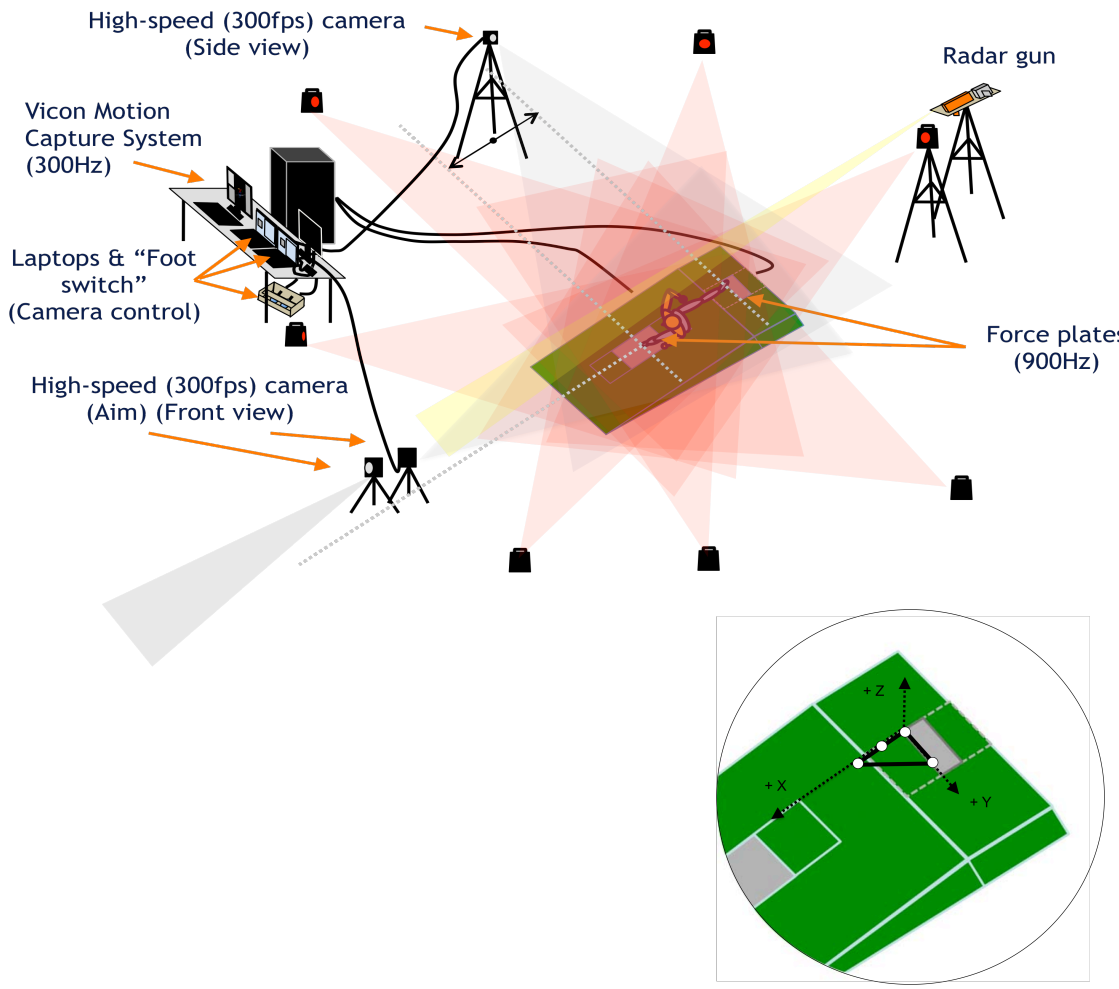



**Figure 9**. Laboratory equipment set up

A modified version of the pitching qualitative analysis protocol developed by the American Sports Medicine Institute (ASMI) was used to qualitatively evaluate the pitcher's technique from the frontal and sagittal view videos (**Appendix 1**).[126, 147] The original assessment tool developed by ASMI (**Appendix 2**) is a 24-item checklist of what is considered a "proper" technique based on a large database of kinematic data.[126, 147] While it has been reported that only 4 out of 24 parameters demonstrate good validity (Kappa > 0.41) against the ratings based on the data captured using a three-dimensional motion analysis system, it has also been reported that 22 out of the 24 parameters demonstrate good (Kappa

>0.41) intra-rater agreements.[147] This form was the only qualitative analysis protocol currently available that allowed systematic evaluation of a pitching technique without the use of laboratory-based motion analysis systems. Upon reviewing the evaluation form, we identified several items that pertained to more than 1 aspects of the movement (ex. timing and position of the segment). Therefore, we revised those items so that each movement aspect was graded individually. The modified version of the evaluation tool included 30-items, and the number of properly performed movements (out of 30) were used to represent the quality of pitcher's technique. Justification for modifying the items are presented in **Appendix 3**.

## 3.4 Procedures

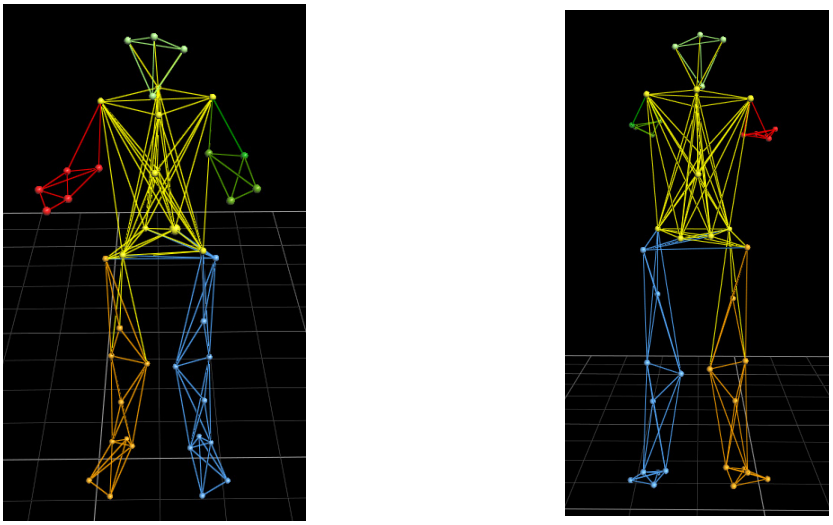
### *3.4.1 Testing Preparation*

The data collections took place at the Sports Medicine Research Laboratory housed within the Department of Exercise and Sport Science at the University of North Carolina at Chapel Hill. The participants were explained on the general purpose of the study (i.e. effects of a pitching technique on joint loading and performance), yet were blinded to the *specific* technical parameters (i.e. *trunk movement*) that were being evaluated until the end of the study. This was done so that the pitcher's performance would not be influenced by the knowledge of the specific purpose of the study. After obtaining an informed consent/assent, participant's demographics (age, limb dominance, years of experience) and injury history were captured using a questionnaire. Subsequently the participant changed into a tight-fitting clothing, and the anthropometric measures were taken using a statiometer, scale, anthropometer (caliper), and a tape measure. The measurements were used for the reporting

of participant demographics, estimation of inertial characteristics of the body segments, and normalization of the kinetic variables. The specific anthropometric parameters measured included height, body mass, arm length (acromion to elbow joint), forearm length (radial head to radial styloid process), maximum arm/forearm circumference, and breadth of an elbow, wrist, and hand.[38] The limb measures were taken on the pitcher's dominant limb.

The participant proceeded to warm-up as they normally would before practices/games (ex. jog, stretch, warm up throws etc.). Unrestricted time was given to the participants to ensure they were adequately warmed up. Once the warm up was complete, 40 reflective markers were secured onto the participant's anatomical landmarks using a double-sided tape, pre-wrap, and an athletic tape. The specific anatomical landmarks for the marker placements were as follows: chin, sternal notch, spinous process of the 7th cervical spine (C7), xyphoid process, spinous process of the 8th thoracic spine (T8), 3rd matacarpal on the throwing hand, and bilateral radial/ulnar styloid process, medial/lateral elbow epicondyle, acromion process, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), greater trochanter, anterior thigh, medial/lateral knee epicondyle, anterior shank, medial/lateral malleolus, 5th metatarsal styloid process, and 1st metatarsal head. The marker locations were selected based on the recommendation from the International Society of Biomechanics (ISB).[212, 213] In addition, the pitcher was fitted with an adjustable headband (Full 90 Sports Inc., San Diego, CA) with three markers attached to the front, right, and left side of the head. Once fitted with the reflective markers, the participant stood in the capture volume with their feet shoulder-width apart, arms flexed to 90°, elbows kept straight, and palms facing upward, for a capturing of the static trial (**Figure 10**). Following the static trial, the markers on the chin, medial knee, medial malleolus, and 1st metatarsal head were removed. The participant then

performed 5-10 sub-maximal pitches to get used to pitching with the reflective markers attached to the body.



Anterior View Posterior View

**Figure 10**. Static marker placement for the right-handed pitchers. For the left-handed pitchers, the marker on the right 3rd metacarpal was placed on the left 3rd metacarpal.

*3.4.2 Pitching Trial*

Once the preparation and warm up were complete, the pitcher was instructed to perform fast pitches from a wind up, and to pitch as fast and as accurately as possible while aiming at the "X" marked on the center of the strike zone. In this study, the pitches were counted (i.e. considered a qualified pitch) if the ball hit the backstop. In another words, pitches were excluded if it missed the backstop. Furthermore, the pitches were considered a strike if they hit the "strike zone" on the backstop (0.64m H X 0.38m W rectangle on the backstop). The pitcher continued to pitch until a minimum of 5 qualified pitches and a minimum of 3 strike pitches were captured. The pitcher was given 30-60 second rest in

between pitches. For each pitch, kinematic and kinetic data, videos of the pitching trial (frontal and sagittal views), a video of the ball strike, and ball speed were captured.

After the pitching trials, videos from the pitcher's three fastest strike pitches were reviewed by the two primary raters (SO & JW), in order to determine the presence of the technical errors. If the ratings from the two raters did not match, the third rater was asked to review the video. The disagreement between the two primary raters occurred in 4.1% of all pitches for OS, 2.7% of all pitches for BLSFC, 4.1% of all pitches for LLSFC, 5.9% of all pitches for LLMER, and 2.7% of all pitches for FT. The raters first identified the frames with an instant of stride foot contact, maximal shoulder external rotation, and ball release in frontal and/or sagittal view videos. The instant of stride foot contact was identified as the frame when any part of the foot touched the mound. The instant of the maximal shoulder external rotation was estimated as the frame when the shoulder appeared to be most externally rotated. The instant of ball release was identified as the first frame the ball became separated from the hand. The raters then determined if the pitcher demonstrated the error in the identified frames based on the descriptions of the technical errors (**Figures 2-6**). In order to aid in identification of the errors, the raters placed a transparency with 2 lines (vertical and 20° inclined) (**Figure 11**) over the computer monitor while rating the pitches. For each pitching trial, the errors were considered to be present when the errors were identified by 2 or more raters. The pitcher was determined to have the errors, if they were identified in at least two of the three pitches.

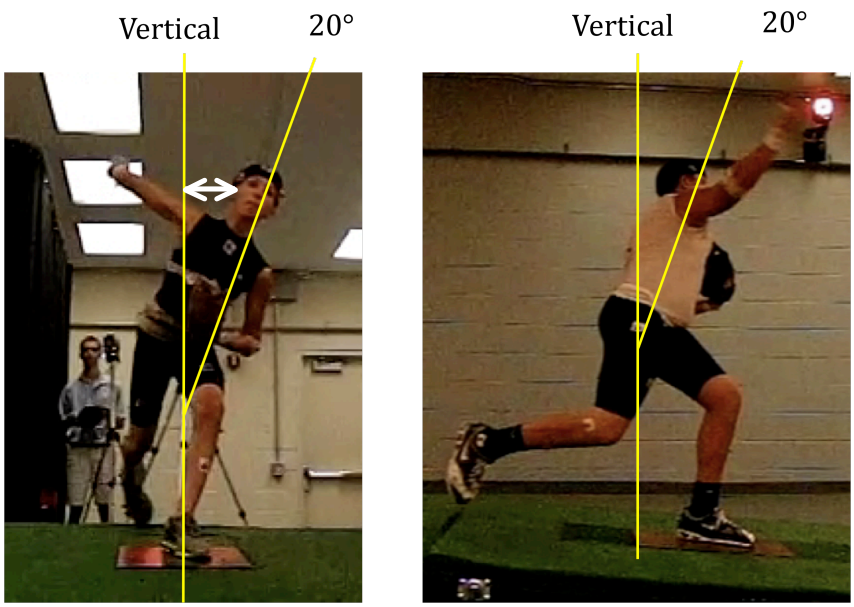



**Figure 11:** Use of reference lines on a transparency to aid in rating of the technical errors

Prior to this study, the investigators selected three random pitches (out of 10) performed by the pilot test participants (42 high school pitchers), and rated the pitches for the technical errors. Out of 42 pitchers, 36 pitchers consistently demonstrated the same pattern of errors (or lack of) in all three pitches. In six pitchers, the errors were not consistently present in all three pitches. However, upon closer observation, we observed that the inconsistent errors were on the border of being classified as error/no-error. This observation indicated that the technical errors are constant characteristics demonstrated by pitchers, and not dependent on selection of pitches.

Using the same three trials from the 42 pitchers, the investigators established an inter-rater and inter-rater reliability of the error ratings. The intra-rater reliability was established from the ratings from a single rater (SO), that were rated 1 month apart. The inter-rater reliability was established from the ratings from the two primary raters (SO and JW). The Kappa agreement statistics from these analyses are presented in **Table 3**. The inter-rater

agreement of LLSFC was lower compared to the agreement for the other errors. This may be attributed to difficulty in discerning whether or not the pitcher's face overlapped with the vertical line crossing the pitcher's umbilicus. For this reason, transparency with a vertical line was placed over the computer display to aid in error identification for the study trials.

**TABLE 3**. Intra-rater and inter-rater agreement of the technical errors *using pilot data*

| | Intra-rater (κ) | Inter-rater (κ) |
|---|---|---|
| Open shoulder (OS) | .806 | .760 |
| Backward lean at stride foot contact (BLSFC) | .906 | .861 |
| Lateral lean at stride foot contact (LLSFC) | .687 | .440 |
| Lateral lean at maximal shoulder external rotation (LLMER) | .849 | .813 |
| Inadequate forward tilt (FT) | .951 | .734 |

## 3.5 Data Processing

### *3.5.1 Biomechanical variables*

Raw three-dimensional coordinate data were filtered using a 4th order dual pass Butterworth filter using a cut-off frequency of 17Hz.[216] The filtered coordinate data were used for calculations of upper extremity and trunk kinematic and kinetic variables. The anatomical coordinate system of the pelvis, upper torso, arm, and forearm segments were defined based on ISB recommendation, and are described in **Table 4**.[212, 213] The shoulder joint center was defined as the point 17% of the upper arm length from the acromion process in the direction of the negative thorax longitudinal axis, after taking the radius of the reflective marker (0.45cm) into account (**Figure 12**).[167, 206] The elbow and wrist joint centers

were defined as the centroid of the medial and lateral epicondyles, and radial and ulnar styloid processes, respectively.

**TABLE 4:** Definition of anatomical reference frames

| **TABLE 4** | | |
|---|---|---|
| | | **Definition** |
| Upper torso | x | Cross product of y and z vectors |
| | y | Cross product of the z and intermediate vectors |
| | z | Vector extending from midpoint between XYP and T8 to midpoint between SN and C7 markers |
| | Intermediate | Vector extending from midpoint between XYP and T8 to SN |
| Pelvis | x | Cross product of y and z vectors |
| | y | Vector extending from right to left ASIS |
| | z | Cross product of y and intermediate vectors |
| | Intermediate | Vector extending from right ASIS to left PSIS |
| Arm | x | Cross product of y and intermediate vectors |
| | y | Vector extending from elbow joint center to shoulder joint center |
| | z | Cross product of x and y vectors |
| | Intermediate | Vector extending from elbow joint center to wrist joint center |
| Forearm | x | Cross product of y and z vectors |
| | y | Vector extending from ulnar styloid to elbow joint center |
| | z | Cross product of y and intermediate vectors |
| | Intermediate | Vector extending from ulnar styloid process to radial styloid process |
| Hand | x | Cross product of y and z vectors |
| | y | Vector extending from 3$^{rd}$ metacarpal head marker to wrist joint center |
| | z | Cross product of intermediate and y vectors |
| | Intermediate | Vector extending from 3$^{rd}$ metacarpal head marker to ulnar styloid process |

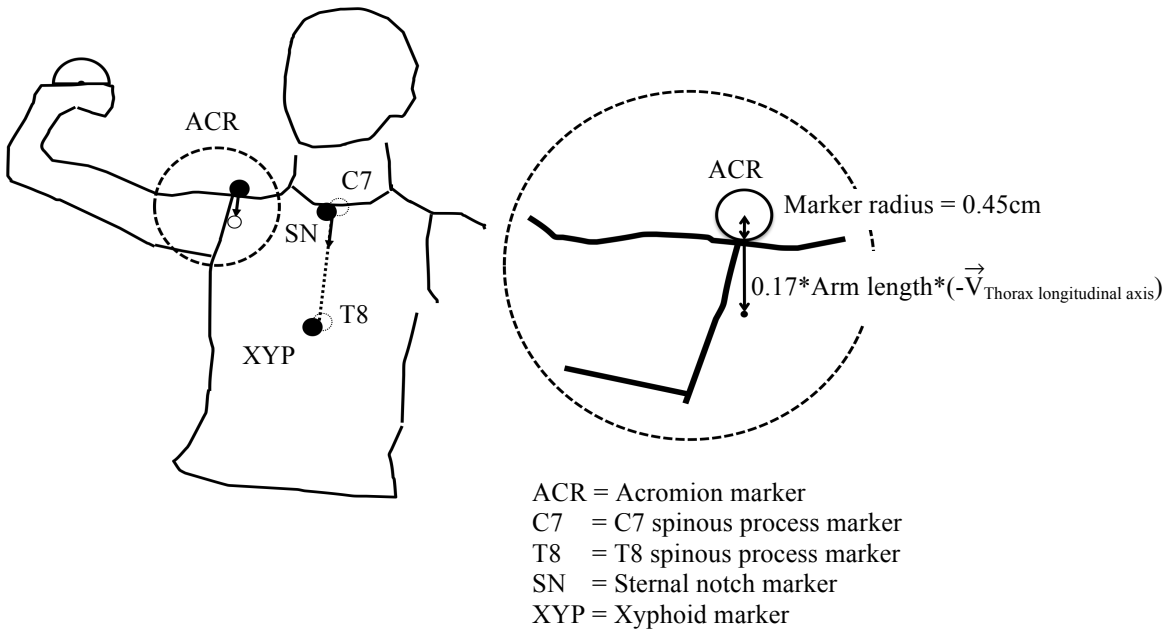



**Figure 12**. Estimation of the shoulder joint center

The orientation of pelvis in the global reference frame was calculated using a Cardan angle of z-x'-y". The first rotation was the rotation about the vertical axis (z-axis) ((+) right/(-)left rotation), the second rotation was the rotation about the anterior-posterior axis (x-axis) of the pelvis ((+) right/(-) left lateral flexion), and the third rotation was the rotation about the medial-lateral axis (y-axis) of the pelvis ((+) flexion/(-) extension). Similarly, the orientation of the upper torso in the global reference frame was calculated using a Cardan angle of z-x'-y". The first rotation was the rotation about the vertical axis (z-axis) ((+) right/(-)left rotation), the second rotation was the rotation about the anterior-posterior axis (x-axis) of the upper torso ((+) right/(-) left lateral flexion), and the third rotation was the rotation about the medial-lateral axis (y-axis) of the upper torso ((+) flexion/(-) extension).

The shoulder joint angles were calculated as the orientation of the arm segment relative to the thorax using a Cardan angle rotation order of y-x'-z".[206] The first rotation was about the longitudinal axis (y-axis) of the thorax ((+) horizontal adduction/(-) horizontal

abduction), the second rotation was about the anterior-posterior axis (x-axis) of the arm ((+) depression/(-) elevation), and the third rotation was about the longitudinal axis (z-axis) of the arm ((+) internal/(-) external rotation). The sign for the shoulder depression/elevation angle was then reversed for the ease of clinical interpretation of the angle ((+) elevation/(-) depression). The shoulder angles are described in **Figure 13**.

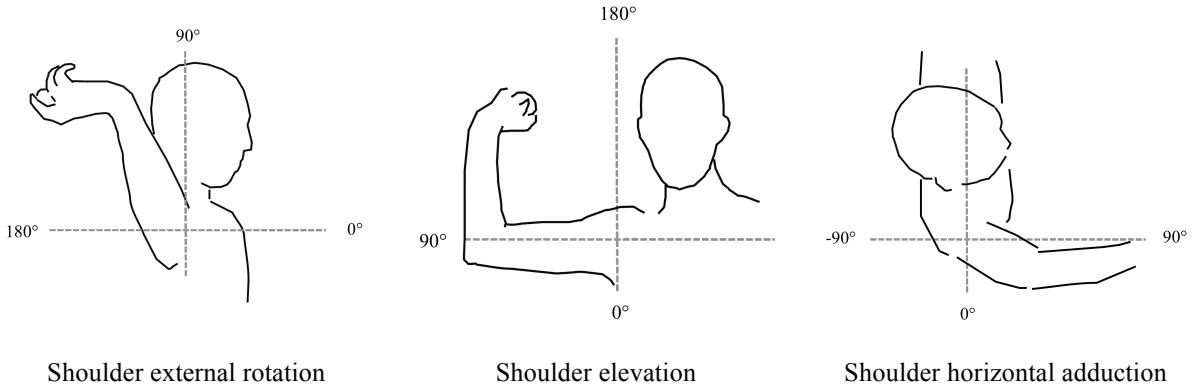



**Figure 13**. Definition of the shoulder angles

The elbow joint angles were calculated as orientations of the forearm segment in the arm reference frame using a Cardan angle sequence of x-z'-y". The first rotation was about the medial-lateral axis (x-axis) of the arm ((+) extension/(-) flexion), the second rotation was about the anterior-posterior axis (z-axis) of the arm ((+) valgus/(-) varus), and the third rotation was about the longitudinal axis (y-axis) of the arm ((+) pronation/(-) supination). The elbow angles are described in **Figure 14**.

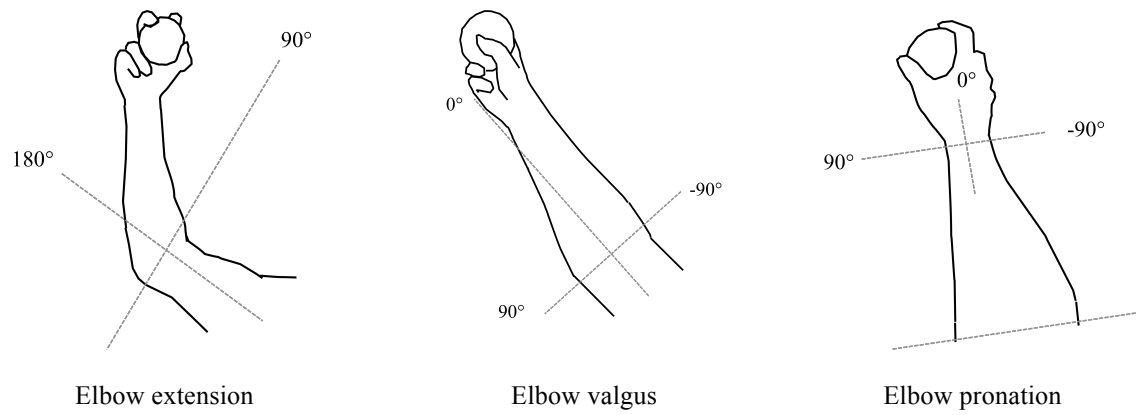



**Figure 14**. Definition of the elbow joint angles

The angular velocities of the joints and segments were calculated by first computing the time derivatives of the angle data. The angular velocity of the first rotation ($\omega_1$) was calculated as the time derivative of the angle data about the first axis of rotation. The angular velocity of the second rotation ($\omega_2$) was calculated as the sum of the time derivative of the angle data about the second axis of rotation and the component of $\omega_1$ that was transformed by the 1st rotation matrix. The angular velocity of the third rotation ($\omega_3$) was calculated as the sum of the time derivative of the angle data about the third axis of rotation and the component of $\omega_2$ that was transformed by the 2nd rotation matrix. The angular velocities about the three axes of rotation were calculated through decomposition of $\omega_3$ along the three anatomical axes.[209]

The joint kinetics were calculated using an inverse dynamics.[209] The segment mass and location of the center of mass (COM) of the hand, forearm, and arm segments were estimated using the estimation method developed by Clauser et al (**Appendix 4**).[38] For each segment, the radi of gyration about the COM in the frontal and sagittal planes were estimated

based on the estimation method described by Dempster et al (**Appendix 5**).[47] The radius of gyration about the longitudinal axis of the segments were considered negligible. In this study, we were unable to place the marker on the ball. Therefore, the linear acceleration of the marker on the 3rd metacarpal head was used as an estimation of the linear acceleration of the ball. Subsequently, the external force acting on the hand was calculated from the mass (0.0145kg) and linear acceleration of the ball, and was assumed to be acting on the hand COM.

The joint reaction forces at the shoulder and elbow joints were initially calculated in the global reference frame, and then transformed into respective reference systems for the calculation of anatomically relevant force components.[209] The elbow joint forces were described as the internal forces acting on the proximal forearm in the elbow joint reference frame. The elbow joint reference frame was defined as follows: y-axis defined as a vector extending from the wrist joint center to the elbow joint center, intermediate axis defined as a vector extending from the wrist joint center to the medial epicondyle, z-axis defined as a cross product of the intermediate and y vectors, and x-axis defined as a cross product of the y and z vectors. The shoulder joint forces were described as the internal forces acting on the proximal arm in the arm reference frame (**Table 4**).

The joint moments at the elbow and shoulder joints were calculated based on the joint reaction forces at the proximal and distal end of the segment, joint moment at the distal end of the segment, segment angular velocity and acceleration about the segment COM, and the inertial characteristics of the segment. The segment angular velocity about the segment COM was calculated from the 1st time derivative of the Euler parameters computed from the direct cosine matrix of the segment. Similarly, the angular acceleration about the segment COM

was calculated from the 2nd time derivative of the Euler parameters. The joint moments were calculated in the segment reference frame using the Euler's Three-dimensional Equations of Motion described below.

$$\Sigma M_x = I_x * \alpha_x + (I_z - I_y) * \omega_y * \omega_z$$

$$\Sigma M_y = I_y * \alpha_y + (I_x - I_z) * \omega_z * \omega_x$$

$$\Sigma M_z = I_z * \alpha_z + (I_y - I_x) * \omega_x * \omega_y$$

The elbow joint moments were calculated described as the internal moments acting on proximal forearm transformed into the elbow joint reference frame. The moment about the elbow x-axis represented (+) extension/(-) flexion, y-axis represented (+) pronation/(-) supination, and z-axis represents (+) varus/(-) valgus moments. The shoulder internal rotation moment was described as the internal moments acting on the proximal arm about the y-axis of the arm reference frame ((+) internal rotation/(-) external rotation moment). The shoulder internal rotation moment was subtracted from the resultant proximal arm moments, and the remaining moments were transformed into the thorax anatomical reference frame so that the remaining moments can be described in the cardinal planes (frontal, sagittal, and transverse planes) within the thorax reference frame. The moment about the thorax x-axis represented (+) adduction/(-) abduction, y-axis represented (+) extension/(-) flexion, and z-axis represented (+) horizontal adduction/(-) horizontal abduction moments. In order to facilitate the comparisons of joint kinetics among the pitchers of different body size, the joint forces were normalized to the pitcher's body weight (= body mass(kg)*9.81(m/sec$^2$)), and the joint moments were normalized to the product of the pitcher's height (m) and body weight.

The critical time points during pitching (i.e. stride foot contact, instant of maximal shoulder external rotation, and ball release) were identified for the calculation of specific dependent variables (**Tables 1 & 2**). The stride foot contact was identified as an instant when the vertical ground reaction force from the stride foot exceeded 10N.[45, 46] The instant of the maximal shoulder external rotation was determined using the joint angle data. The instant of ball release was determined as the $4_{th}$ frame after the wrist surpassed the elbow in the global X-axis direction (direction of throw). This definition (modification of the method described by Escamilla et al[61]) was based on the observations of the sagittal view videos (300 frames per second) from the first 15 pitchers. We determined that the ball release occurred within 3-5 frames after the wrist surpassed the elbow in the direction of throw in all pitches, with the release occurring on the $4^{th}$ frame in over 60% of the pitching trials. For the calculation of the timing variables, the pitching motion between the stride foot contact and ball release were normalized to 100% pitch cycle. All dependent variables were calculated as the mean of the three fastest strike pitches. All calculations were conducted using a custom-written Matlab program (MathWorks Inc., Natick, MA).

*3.5.2 Qualitative analysis of a pitching technique*

The principal investigator (SO) and a research assistant (JL) who was blinded to the purpose of the study reviewed the videos to qualitatively evaluate the pitcher's technique using the modified version of the ASMI pitching quality assessment tool (**Appendix 2**).[126, 147] The two raters evaluated the pitcher's technique independently, by reviewing the frontal and sagittal views of the fastest strike pitch. The videos from the $2^{nd}$ and $3^{rd}$ fastest pitches were also reviewed, when the raters were unsure of the ratings from the fastest pitch. For each

item, when the ratings from the two raters did not match, the raters reviewed the videos together to decide on the final ratings. The proportion of the pitches with disagreements ranged from 5.5% to 34.2% for each item.

*3.5.3 Performance measures*

The ball speed was calculated as an average of the three fastest pitches recorded using a radar gun. The pitch accuracy was calculated from the first five qualifying pitches. For each pitch, the last frame before the ball hit the target was identified and exported as an image file using Image J (National Institute of Health, Bethesda, MD) software. The ball and four corners of the strike zone were digitized on the exported image (**Figure 15**). The points on the upper corners (1 and 2 in **figure 15**) defined the horizontal axis, and the points on the left upper and lower corners (1 and 3 in **figure 15**) defined the vertical axis. The center of the strike zone was calculated as the average position of the 4 corners. The absolute, vertical, and horizontal distances between the ball and the center of the strike zone were calculated for each pitch.


**Figure 15**. Digitization of the backstop to calculate ball accuracy

### 3.6 Data Analysis

Independent t-tests were used to compare the upper extremity kinetic variables (SA1a), ball speed (SA1b), ball accuracy (SA1c), and quality of pitching technique (SA1d) between the pitchers with and without each technical error (OS, BLSFC, LLSFC, LLMER FT). For the comparison of the upper extremity kinetic variables (SA2a), ball speed (SA2b), ball accuracy (SA2c), and quality of pitching technique (SA2d) among the pitchers with 0, 1, 2, and 3 technical errors, one-way ANOVA followed by Bonferroni post hoc tests were conducted for each variable.

Additionally, reliability (agreement) and validity of the independent and dependent variables were assessed. The inter-rater agreement of the technical errors and the items in the modified qualitative assessment of pitching technique were assessed using the Kappa statistics of agreement. The reliability of the biomechanical variables and ball speed were assessed using the intra-class correlation coefficient and the standard error of measurement. The agreement between the error ratings and the ratings based on the coordinate data from the motion capture system (validity of the rating) were assessed using the Chi-square statistics of association.

For the technical errors that were associated with increased joint loading based on the observations from the specific aim 1, kinematic variables were compared between the pitchers with and without the error, using separate independent t-tests. Additional secondary analyses were conducted to supplement the above mentioned analyses. The rationale and statistical procedures used for these analyses are described in chapter 4. An a-priori alpha level was set at 0.05. Statistical analysis were conduced using SAS Enterprise 9.3 (SAS Institute Inc., Cary, NC).

# CHAPTER 4

# RESULTS

## 4.1 Introduction

The primary purpose of this study was to examine the effects of observable technical errors of the trunk on joint loading, pitching performance, and quality of pitching technique in high school baseball pitchers. The *original* specific aims and hypotheses were:

**Specific Aim 1:** To compare the (a) upper extremity joint kinetic variables (peak shoulder proximal force, peak shoulder internal rotation moment, and peak elbow varus moment), (b) ball speed, (c) accuracy, and (d) quality of pitching technique between the high school pitchers who demonstrate the technical errors at 0, 1, and 2 or more critical time points (stride foot contact, maximal shoulder external rotation, and ball release).

**Hypothesis 1:** Pitchers who demonstrate technical errors at a greater number of time points will demonstrate (a) a greater joint loading, (b) lower ball speed, (c) lower accuracy, and (d) lower overall quality of pitching technique.

**Specific Aim 2**: To compare the (a) upper extremity joint kinetics (peak shoulder proximal force, peak elbow varus moment, and peak shoulder internal rotation moment), (b) ball speed, (c) accuracy, and (d) quality of pitching technique between

the high school pitchers who demonstrate technical errors at each critical time point and the pitchers who do not demonstrate the technical errors at any critical time point.

**Hypothesis 2:** The pitchers with the technical errors at each critical time point will demonstrate (a) greater joint loading, (b) lower ball speed, (c) lower accuracy, and (d) lower quality of pitching technique compared to the pitchers who do not demonstrate technical errors at any critical time point.

However, these original two specific aims and hypotheses were revised due to a small number of pitchers who demonstrated two of the five technical errors that were examined in this study (open shoulder and inadequate forward trunk tilt), and to avoid repeated comparisons of the dependent variables against the group of pitchers with no technical errors when addressing the specific aim 2. Additionally, we decided to include a peak elbow proximal force, peak elbow extension moment, and peak shoulder anterior force in the list of kinetic dependent variables of interest. The *revised* specific aims and hypotheses are (changes underlined):

**Specific Aim 1**: To compare the (a) upper extremity joint loading (peak elbow proximal force, peak shoulder anterior force, peak shoulder proximal force, peak elbow varus moment, peak elbow extension moment, and peak shoulder internal rotation moment), (b) ball speed, (c) accuracy, and (d) quality of pitching technique between the high school pitchers with and without 1) open shoulder (OS), 2) backward lean at stride foot contact (BLSFC), 3) lateral lean at stride foot contact

(LLSFC), 4) lateral lean at maximal shoulder external rotation (LLMER), and 5) inadequate forward trunk tilt at ball release (FT).

**Hypothesis 1:** The pitchers with each technical error will demonstrate (a) greater joint loading, (b) lower ball speed, (c) lower accuracy, and (d) lower quality of pitching technique compared to the pitchers who do not demonstrate the technical errors.

**Specific Aim 2:** To compare the (a) upper extremity joint loading (peak elbow proximal force, peak shoulder anterior force, peak shoulder proximal force, peak elbow varus moment, peak elbow extension moment, and peak shoulder internal rotation moment), (b) ball speed, (c) accuracy, and (d) quality of pitching technique among the high school pitchers who demonstrate 0, 1, 2, and 3 technical errors.

**Hypothesis 2:** The pitchers who demonstrate a greater number of technical errors will demonstrate (a) greater joint loading, (b) lower ball speed, (c) lower accuracy, and (d) lower quality of pitching technique.

In addition to these specific aims, secondary analyses were conducted to supplement the observations from specific aims 1 and 2. These analyses included:

- Association between lateral lean at maximal shoulder external rotation (LLMER) and a recent history of pitching-related upper extremity injuries (see **4.7**)
- Comparisons of the kinematic variables between the pitchers with and without lateral lean at maximal shoulder external rotation (LLMER) (see **4.8**)
- Effects of the technical errors at stride foot contact (OS, LLSFC, and BLSFC) and stride foot offset on lateral lean at maximal shoulder external rotation (LLMER) (see **4.9**)
- Relationships between the trunk kinematics at stride foot contact and maximal shoulder external rotation (see **4.10**)

- Effects of forward trunk tilt at ball release on the performance measures and the joint loading (see **4.11**)
- Comparisons of the kinematic variables between the pitchers with inadequate, normal, high, and excessive forward trunk tilt (see **4.12**)

## 4.2 Reliability and Validity of the Dependent and Independent Variables

### *4.2.1 Inter-rater Agreement of the Technical Errors*

In this study, presence of the technical errors were determined by the ratings from 3 raters. The two primary raters (SO & JW) independently rated the videos of the three fastest strike pitches for all pitchers. The raters determined pitchers to have specific errors when the errors were identified in two or more out of the three pitches. When the two raters disagreed on the ratings, the ratings from the third rater (JM) were used to determine the presence of errors. Prior to running statistical analyses, inter-rater agreements (between SO & JW) for each technical error were assessed using the Kappa statistics (**Table 5**). The inter-rater agreement was moderate (Kappa: 40-60%) for OS, and excellent (Kappa: >80%) for the other technical errors (BLSFC, LLSFC, LLMER, and FT).[114]

**TABLE 5**: Inter-rater agreement of the technical errors

| **TABLE 5** | Kappa | Max Kappa |
|---|---|---|
| Open shoulder (OS) | 0.41 | 0.88 |
| Lateral lean at stride foot contact (LLSFC) | 0.89 | 0.92 |
| Backward lean at stride foot contact (BLSFC) | 0.90 | 0.97 |
| Lateral lean at maximal shoulder external rotation (LLMER) | 0.94 | 0.94 |
| Inadequate forward tilt at ball release (FT) | 0.88 | 0.88 |

*4.2.2 Validation of Technical Errors*

The final error ratings for each technical error were validated using the three-dimensional coordinate data from the motion capture system (**Table 6**). The parameters used to validate each error are described in **table 6** and **figures 16-20**. The Kappa statistics between the visual ratings and the ratings based on the coordinate data are also provided in **table 6**. The agreement was substantial (Kappa = 60-80%) for LLSFC and moderate (Kappa = 40-60%) for OS, BLSFC, LLMER, and FT.

**Table 6**: Validation of rated technical errors

| Table 6 | | | | |
|---|---|---|---|---|
| Technical errors | Definition | Cut off | Kappa | Max Kappa |
| Open shoulder | Position of the front shoulder joint center relative to the back (throwing) shoulder joint center in the global Y-Z plane (frontal view) at stride foot contact | < 15cm | 0.579 | 0.748 |
| Backward lean at SFC | Position of the head center relative to the stride foot ankle joint center in the global Y-Z plane (frontal view) at stride foot contact | > 0cm | 0.528 | 0.891 |
| Lateral lean at SFC | Position of the head center relative to the mid-ASIS markers in the global X-Y plane (sagittal view) at stride foot contact | < -10cm | 0.700 | 0.900 |
| Lateral lean at MER | Position of the head center relative to the stride foot ankle joint center in the global Y-Z plane (frontal view) at maximal shoulder external rotation | > 15cm | 0.536 | 0.826 |
| Inadequate forward trunk tilt | Angle of the longitudinal axis of the thorax projected onto the global X-Y plane (sagittal view) at ball release | < 20° | 0.579 | 0.748 |

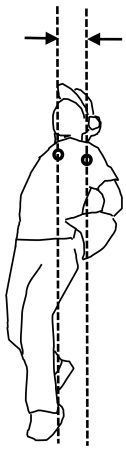


**Figure 16**. Illustration of the position of the front shoulder relative to the back (throwing) shoulder. The horizontal displacement was used to validate the open shoulder (OS).

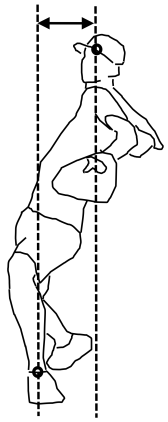


**Figure 17.** Illustration of the head position relative to the stride foot ankle. The horizontal displacement was used to validate the backward lean at stride foot contact (BLSFC).

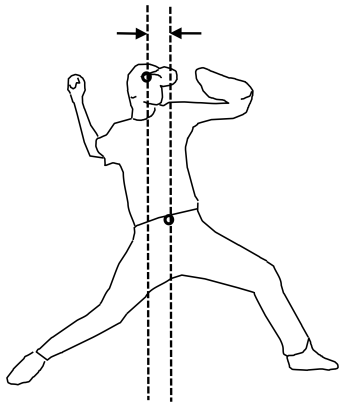


**Figure 18.** Illustration of the head position relative to the mid-ASIS points. The horizontal displacement was used to validate the backward lean at stride foot contact (LLSFC).

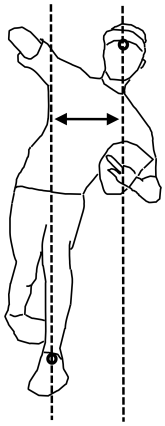


**Figure 19.** Illustration of the head position relative to the stride foot ankle. The horizontal displacement was used to validate the lateral lean at maximal shoulder external rotation (LLMER).

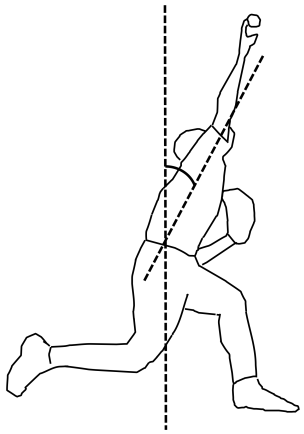


**Figure 20.** Illustration of the forward trunk tilt angle relative to vertical. The angle was used to validate the inadequate forward trunk tilt (FT).

*4.2.3 Reliability of the Ball Speed, Quality of Pitching Technique, and Biomechanical Variables*

Reliability of the ball speed, kinematic, and kinetic variables were assessed using the intraclass correlation coefficients ($ICC_{2,1}$) and the standard error of measurements (SEM). The quality of pitching technique was assessed as the total score of the modified American Sports Medicine Institute pitching evaluation form (**Appendix 1**). The inter-rater agreements of each item in the evaluation form were assessed using the Kappa statistics.

The reliability of ball speed and kinematic variables are presented in **table 7**, and the reliability of kinetic variables are presented in **table 8**. The inter-rater agreements of the 30 items in the pitching evaluation form were excellent (>80%) for 7 items, substantial (60-80%) for 9 items, moderate (40-60%) for 7 items, and poor (<40%) for 7 items. All kinematic and kinetic variables demonstrated high reliability as indicated by the high ICC (> 0.80) and low SEM values.[114]

**TABLE 7:** Reliability of the ball speed and kinematic variables

| **TABLE 7** | | |
|---|---|---|
| | ICC $_{2.1}$ | SEM |
| Ball speed (m/sec) | .981 | 0.43 |
| | | |
| Stride foot contact | | |
| Upper torso rotation angle (°) | .798 | 3.09 |
| Upper torso lateral tilt angle (°) | .972 | 1.26 |
| Upper torso flexion angle (°) | .956 | 2.49 |
| Pelvis rotation angle (°) | .886 | 4.23 |
| | | |
| Maximal shoulder external rotation | | |
| Upper torso rotation angle (°) | .975 | 2.00 |
| Upper torso lateral tilt angle (°) | .969 | 1.71 |
| Upper torso flexion angle (°) | .985 | 1.56 |
| Shoulder elevation angle (°) | .958 | 1.51 |
| Shoulder external rotation angle (°) | .994 | 1.45 |
| Shoulder horizontal abduction angle (°) | .991 | 1.32 |
| Elbow extension angle (°) | .960 | 2.74 |
| | | |
| Ball release | | |
| Upper torso rotation angle (°) | .984 | 1.88 |
| Upper torso lateral tilt angle (°) | .981 | 1.65 |
| Upper torso flexion angle (°) | .987 | 1.57 |
| Shoulder horizontal abduction angle (°) | .987 | 1.40 |
| Shoulder elevation angle (°) | .955 | 1.66 |
| Elbow extension angle (°) | .953 | 1.06 |
| | | |
| Peak velocity | | |
| Upper torso rotation velocity (°/sec) | .987 | 19.9 |
| Shoulder horizontal adduction velocity (°/sec) | .947 | 30.8 |
| Shoulder internal rotation velocity (°/sec) | .924 | 228.9 |
| Elbow extension velocity (°/sec) | .947 | 43.1 |
| | | |
| Temporal variables | | |
| Peak upper torso rotation velocity (%) | .888 | 3.44 |
| Initiation of upper torso rotation (%) | .887 | 5.00 |
| Maximal shoulder external rotation (%) | .840 | 1.18 |

ICC = Intraclass correlation coefficient, SEM = Standard error of measurement

**TABLE 8**: Reliability of the shoulder and elbow kinetic variables

| TABLE 8 | | |
|---|---|---|
| | ICC $_{2.1}$ | SEM |
| Peak elbow proximal force (%BW) | .974 | 2.57 |
| Peak elbow varus moment (%BW*height) | .971 | 0.14 |
| Peak elbow extension moment (%BW*height) | .829 | 0.31 |
| Peak shoulder anterior force (%BW) | .976 | 0.94 |
| Peak shoulder proximal force (%BW) | .982 | 2.41 |
| Peak shoulder internal rotation moment (%BW*height) | .973 | 0.24 |

ICC = Intraclass correlation coefficient, SEM = Standard error of measurement, BW = Body weight

### 4.3 Demographics

A total of 73 pitchers participated in this study. One participant was excluded from the study, due to an instrumentation error that resulted in a disappearance of markers on the throwing wrist and 3rd metacarpal head during the critical phases of pitching. In addition, accuracy data were missing for 5 participants, due to a malfunction/operation of the camera that was used to film the target. Demographics of a total of 72 participants who were included in the analyses are presented in **table 9**.

**TABLE 9:** Participant demographics

| TABLE 9 | | | |
|---|---|---|---|
| | Mean | SD | Range |
| Height (m) | 1.8 | 0.07 | 1.6-2.0 |
| Mass (kg) | 72.7 | 9.8 | 49.0-93.0 |
| Age (years) | 15.5 | 1.2 | 13-18 |
| Year of baseball experience (years) | 10.0 | 2.0 | 4-13 |
| Year of pitching experience (years) | 6.1 | 1.9 | 2-11 |
| Limb dominance | 56 Right / 16 Left | | |
| History of pitching-related upper extremity injury in past 2 years | 13 Yes / 59 No | | |

### 4.4 Observed Technical Errors

A breakdown of participants with the technical errors are summarized in **figure 21**. The final ratings indicated that 31 pitchers did not demonstrate any technical error and 41 pitchers demonstrated at least 1 technical error. The open shoulder and FT were only present in 4 and 5 pitchers, respectively. The backward lean at stride foot contact (BLSFC), LLSFC, and LLMER were more prevalent, and were demonstrated by 13, 20, and 31 pitchers, respectively. Sixteen pitchers demonstrated 1 error, 18 demonstrated 2 errors, and 7 demonstrated 3 errors. No pitcher demonstrated more than 4 errors. Among the 16 pitchers who demonstrated only 1 error, 2 demonstrated OS, 3 demonstrated LLSFC, 9 demonstrated LLMER, and 2 demonstrated FT. Among the 18 pitchers who demonstrated 2 errors, 13 demonstrated BLSFC and LLMER, 2 demonstrated LLSFC and LLMER, 2 demonstrated LLSFC and FT, and 1 demonstrated OS and FT. Among the 7 pitchers who demonstrated 3 errors, 6 demonstrated BLSFC, LLSFC, and LLMER, and 1 demonstrated OS, BLSFC, and LLMER.

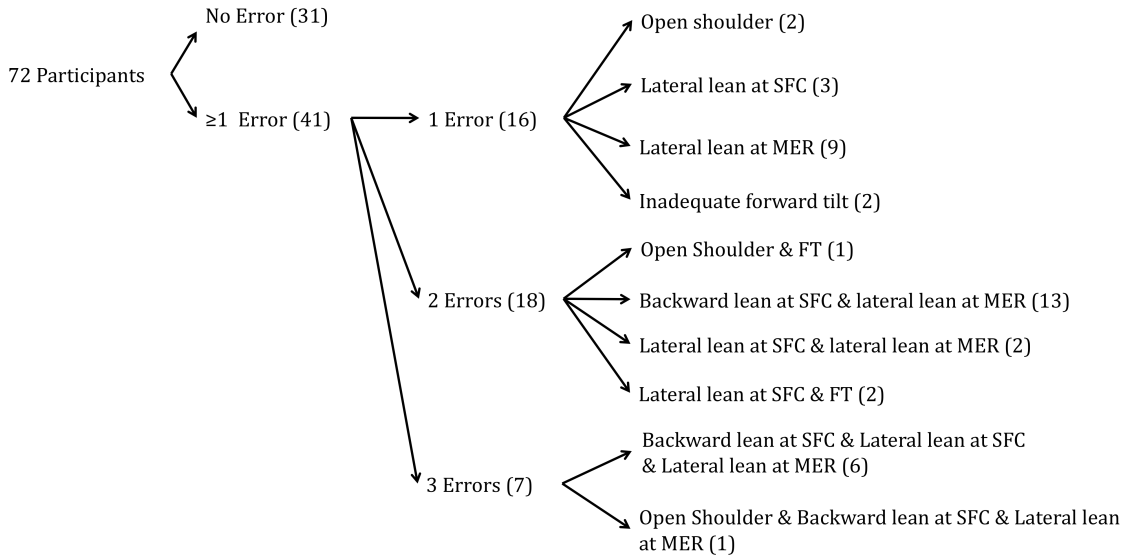



**Figure 21.** Breakdown of participants with the technical errors

### 4.5 Comparisons of the Performance Measures, Quality of Pitching Technique, and Joint Loading between Pitchers with and without the Individual Technical Errors (Specific Aim 1)

In order to examine the effects of each technical error on performance, quality of pitching technique, and joint loading, independent of the other technical errors, the dependent variables were compared between the pitchers with and without 1) OS (**Tables 10 & 11**), 2) BLSFC (**Tables 12 & 13**), 3) LLSFC (**Tables 14 & 15**), 4) LLMER (**Tables 16 & 17**), and 5) FT (**Tables 18 & 19**). Due to a small number of pitchers with OS and FT, many of the comparisons between the pitchers with and without these errors did not meet the normality assumption. Therefore, the non-parametric tests (Mann-Whitney U test) were used to compare the variables between the pitchers with and without OS and FT.

There were no statistically significant differences in any of the variables between the pitchers with and without OS, BLSFC, or LLSFC ($p>0.05$). However, we observed that the pitchers who demonstrated LLMER had a higher ball speed (mean difference = 1.5±2.6, 95%CI = 0.26-2.7, $p = 0.019$), and experienced a greater elbow proximal force (mean difference = 10.7±13.4, 95%CI = 4.4-17.1, $p = 0.001$), shoulder proximal force (mean difference = 10.4±14.9, 95%CI = 3.4-17.5, $p = 0.004$), elbow varus moment (mean difference = 0.45±0.77, 95%CI = 0.08-0.81, $p = 0.017$), and shoulder internal rotation moment (mean difference = 0.47±0.75, 95%CI = 0.11-0.82, $p = 0.011$) compared to the pitchers who did not demonstrate LLMER. No other variables were different between pitchers with and without LLMER ($p>0.05$).

We also observed that the pitchers who demonstrated FT had a lower ball speed ($p=0.011$), quality of pitching technique ($p=0.017$), and proximal joint forces at the shoulder

(p=0.018) and elbow (p=0.014) joints. There were no significant differences in the other variables between the pitchers with and without FT (p>0.05).

**TABLE 10**: Comparisons of the performance measures and the quality of pitching technique between the pitchers with and without open shoulder (OS)

**TABLE 10**

| | Technical error | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=4) | No (n=68) | z | p | Effect size† | Power |
| Ball speed (m/sec) | 30.0±4.2 | 31.4±8.8 | -0.95 | 0.347 | -0.52 | 0.17 |
| Accuracy* | | | | | | |
| Absolute distance (m) | 0.50±0.09 | 0.43±0.09 | 1.38 | 0.168 | 0.74 | 0.30 |
| Horizontal distance (m) | 0.31±0.05 | 0.24±0.08 | 1.53 | 0.126 | 0.86 | 0.38 |
| Vertical distance (m) | 0.35±0.12 | 0.31±0.09 | 0.44 | 0.660 | 0.45 | 0.14 |
| Quality of pitching (pts) | 25.0±3.6 | 25.8±2.6 | -0.34 | 0.738 | -0.30 | 0.10 |

* Accuracy data were missing from 1 pitcher with OS and 4 pitchers without OS
† Cohen's d effect size

**TABLE 11**: Comparisons of the shoulder and elbow peak kinetic variables between the pitchers with and without open shoulder (OS)

**TABLE 11**

| | Technical error | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=4) | No (n=68) | z | p | Effect size† | Power |
| Peak elbow proximal force (%BW) | 86.5±14.4 | 98.4±14.1 | -1.56 | 0.119 | -0.83 | 0.36 |
| Peak elbow varus moment (%BW*Height) | 3.32±0.87 | 4.07±0.78 | -1.54 | 0.124 | -0.94 | 0.44 |
| Peak elbow extension moment (%BW*Height) | 1.45±0.49 | 1.76±0.71 | 0.219 | 0.439 | -0.44 | 0.14 |
| Peak shoulder anterior force (%BW) | 29.3±6.4 | 34.5±6.1 | -1.39 | 0.165 | -0.84 | 0.37 |
| Peak shoulder proximal force (%BW) | 89.9±18.4 | 99.2±15.3 | -0.95 | 0.344 | -0.59 | 0.21 |
| Peak shoulder internal rotation moment (%BW*Height) | 3.27±0.80 | 3.98±0.77 | -1.56 | 0.119 | -0.91 | 0.42 |

BW = Body weight
† Cohen's d effect size

**TABLE 12**: Comparisons of the performance measures and the quality of pitching technique between the pitchers with and without backward lean at stride foot contact (BLSFC)

**TABLE 12**

| | Technical error | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=20) | No (n=52) | t | p | Effect size† | Power |
| Ball speed (m/sec) | 32.6±1.8 | 31.4±2.9 | -1.95 | 0.057 | 0.44 | 0.38 |
| Accuracy* | | | | | | |
| Absolute distance (m) | 0.44±0.09 | 0.43±0.10 | -0.42 | 0.678 | 0.11 | 0.07 |
| Horizontal distance (m) | 0.23±0.09 | 0.25±0.08 | 1.11 | 0.269 | -0.25 | 0.15 |
| Vertical distance (m) | 0.33±0.08 | 0.31±0.09 | -1.06 | 0.293 | 0.23 | 0.14 |
| Quality of pitching (pts) | 25.9±1.9 | 25.7±2.9 | -0.20 | 0.839 | 0.08 | 0.06 |

* Accuracy data were missing from 1 pitcher with BLSFC and 4 without BLSFC
† Cohen's d effect size

**TABLE 13**: Comparisons of the shoulder and elbow peak kinetic variables between the pitchers with and without backward lean at stride foot contact (BLSFC)

**TABLE 13**

| | Technical error | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=20) | No (n=52) | t | p | Effect size† | Power |
| Peak elbow proximal force (%BW) | 102.0±96.2 | 96.2±14.5 | -1.55 | 0.125 | 0.40 | 0.38 |
| Peak elbow varus moment (%BW*Height) | 4.01±0.56 | 4.04±0.88 | 0.16 | 0.871 | -0.04 | 0.07 |
| Peak elbow extension moment (%BW*Height) | 1.62±0.58 | 1.79±0.74 | 1.90 | 0.371 | -0.24 | 0.15 |
| Peak shoulder anterior force (%BW) | 34.2±5.4 | 34.2±6.5 | -0.01 | 0.990 | 0.00 | 0.33 |
| Peak shoulder proximal force (%BW) | 102.8±15.0 | 97.2±15.8 | -1.38 | 0.173 | 0.36 | 0.05 |
| Peak shoulder internal rotation moment (%BW*Height) | 3.96±0.62 | 3.94±0.88 | -0.13 | 0.898 | 0.03 | 0.15 |

BW = Body weight
† Cohen's d effect size

**TABLE 14**: Comparisons of the performance measures and the quality of pitching technique between the pitchers with and without lateral lean at stride foot contact (LLSFC)

**TABLE 14**

| | Technical error | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=13) | No (n=59) | t | p | Effect size† | Power |
| Ball speed (m/sec) | 31.7±2.8 | 31.8±2.7 | 0.09 | 0.928 | -0.04 | 0.05 |
| Accuracy* | | | | | | |
| Absolute distance (m) | 0.46±0.10 | 0.42±0.09 | -1.04 | 0.301 | 0.43 | 0.27 |
| Horizontal distance (m) | 0.27±0.07 | 0.24±0.08 | -0.87 | 0.385 | 0.37 | 0.22 |
| Vertical distance (m) | 0.34±0.11 | 0.31±0.08 | -1.04 | 0.300 | 0.34 | 0.19 |
| Quality of pitching (pts) | 26.2±1.8 | 25.7±2.8 | -0.70 | 0.483 | 0.19 | 0.09 |

* Accuracy data were missing from 1 pitcher with LLSFC and 4 pitchers without LLSFC
† Cohen's d effect size

**TABLE 15**: Comparisons of the shoulder and elbow peak kinetic variables between the pitchers with and without lateral lean at stride foot contact (LLSFC)

**TABLE 15**

| | Technical error | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=13) | No (n=59) | t | p | Effect size† | Power |
| Peak elbow proximal force (%BW) | 96.9±16.3 | 98.0±14.0 | 0.24 | 0.808 | -0.08 | 0.06 |
| Peak elbow varus moment (%BW*Height) | 3.76±0.67 | 4.09±0.81 | 1.36 | 0.178 | -0.41 | 0.27 |
| Peak elbow extension moment (%BW*Height) | 1.88±0.61 | 1.71±0.72 | -0.79 | 0.431 | 0.24 | 0.12 |
| Peak shoulder anterior force (%BW) | 33.3±5.8 | 34.4±6.3 | 0.57 | 0.571 | -0.18 | 0.09 |
| Peak shoulder proximal force (%BW) | 97.7±17.9 | 99.1±15.3 | 0.28 | 0.778 | -0.09 | 0.06 |
| Peak shoulder internal rotation moment (%BW*Height) | 3.63±0.71 | 4.01±0.78 | 1.60 | 0.113 | -0.49 | 0.35 |

BW = Body weight
† Cohen's d effect size

**TABLE 16**: Comparisons of the performance measures and the quality of pitching technique between the pitchers with and without lateral lean at maximal external rotation (LLMER)

**TABLE 16**

| | Technical error | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=31) | No (n=41) | t | p | Effect size† | Power |
| Ball speed (m/sec) | 32.6±2.2 | 31.1±2.9 | -2.41 | 0.019 | 0.55 | 0.63 |
| Accuracy* | | | | | | |
| Absolute distance (m) | 0.44±0.09 | 0.43±0.10 | -0.11 | 0.912 | 0.11 | 0.07 |
| Horizontal distance (m) | 0.23±0.09 | 0.26±0.07 | 1.37 | 0.175 | -0.37 | 0.33 |
| Vertical distance (m) | 0.33±0.08 | 0.31±0.09 | -0.84 | 0.403 | 0.23 | 0.16 |
| Quality of pitching (pts) | 25.5±2.0 | 25.9±3.0 | 0.64 | 0.527 | -0.15 | 0.10 |

* Accuracy data were missing from 3 pitchers with LLMER and 2 without LLMER
† Cohen's d effect size

**TABLE 17**: Comparisons of the shoulder and elbow peak kinetic variables between the pitchers with and without lateral lean at maximal external rotation (LLMER)

**TABLE 17**

| | Technical errors | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=31) | No (n=41) | t | p | Effect size† | Power |
| Peak elbow proximal force (%BW) | 103.9±12.7 | 93.2±13.9 | -3.37 | 0.001 | 0.75 | 0.87 |
| Peak elbow varus moment (%BW*Height) | 4.29±0.73 | 3.84±0.80 | -2.45 | 0.017 | 0.57 | 0.65 |
| Peak elbow extension moment (%BW*Height) | 4.29±0.73 | 3.83±0.80 | 0.83 | 0.412 | 0.65 | 0.77 |
| Peak shoulder anterior force (%BW) | 35.7±5.8 | 33.1±6.3 | -1.75 | 0.084 | 0.42 | 0.42 |
| Peak shoulder proximal force (%BW) | 104.8±14.1 | 94.3±15.5 | -2.94 | 0.004 | 0.67 | .079 |
| Peak shoulder internal rotation moment (%BW*Height) | 4.21±0.71 | 3.75±0.78 | -2.61 | 0.011 | 0.59 | 0.69 |

BW = Body weight
† Cohen's d effect size

**TABLE 18**: Comparisons of the performance measures and the quality of pitching technique between the pitchers with and without inadequate forward tilt (FT)

| **TABLE 18** | Technical error | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=5) | No (n=67) | z | p | Effect size† | Power |
| Ball speed (m/sec) | 28.4±2.9 | 32.0±2.5 | -2.54 | 0.011 | -1.33 | 0.81 |
| Accuracy* | | | | | | |
| Absolute distance (m) | 0.43±0.07 | 0.43±0.10 | -0.09 | 0.463 | 0.00 | 0.05 |
| Horizontal distance (m) | 0.21±0.08 | 0.25±0.08 | -0.60 | 0.552 | -0.49 | 0.18 |
| Vertical distance (m) | 0.35±0.05 | 0.31±0.09 | 1.10 | 0.272 | 0.45 | 0.16 |
| Quality of pitching (pts) | 23.2±2.2 | 26.0±2.6 | -2.39 | 0.017 | -1.06 | 0.62 |

* Accuracy data were missing from 1 pitcher with FT and 4 pitchers without FT
† Cohen's d effect size

**TABLE 19**: Comparisons of the shoulder and elbow peak kinetic variables between the pitchers with and without inadequate forward tilt (FT)

| **TABLE 19** | Technical errors | | | | | |
|---|---|---|---|---|---|---|
| | Yes (n=5) | No (n=67) | z | p | Effect size† | Power |
| Peak elbow proximal force (%BW) | 80.4±13.4 | 99.1±13.6 | -2.46 | 0.014 | -1.31 | 0.79 |
| Peak elbow varus moment (%BW*Height) | 3.63±0.66 | 4.06±0.80 | -0.91 | 0.36 | -0.54 | 0.21 |
| Peak elbow extension moment (%BW*Height) | 2.33±0.67 | 1.70±0.69 | 0.08 | 0.167 | 0.90 | 0.45 |
| Peak shoulder anterior force (%BW) | 33.1±6.0 | 34.3±6.2 | -0.13 | 0.894 | -0.19 | 0.07 |
| Peak shoulder proximal force (%BW) | 80.2±16.7 | 94.2±15.3 | -2.37 | 0.018 | -0.89 | 0.48 |
| Peak shoulder internal rotation moment (%BW*Height) | 3.37±0.59 | 3.99±0.78 | -1.64 | 0.101 | -0.80 | 0.40 |

BW = Body weight
† Cohen's d effect size

### 4.6 Comparisons of the Performance Measures, Quality of Pitching Technique, and Joint Loading between the Pitchers with a Varying Number of Technical Errors (Specific Aim 2)

In order to examine the cumulative effects of the technical errors on the performance measures, quality of pitching technique, and joint loading, the dependent variables were compared among the pitchers who demonstrated 0, 1, 2, and 3 errors. The analyses demonstrated that there were no significant differences in the performance measures (**Table 20**), quality of pitching technique (**Table 20**), or kinetic variables (**Table 21**) among the pitchers with a varying number of technical errors ($p>0.05$).

**TABLE 20**: Comparisons of the performance measures and quality of pitching technique among the pitchers with 0, 1, 2 and 3 errors

| **TABLE 20** | | | | | | |
|---|---|---|---|---|---|---|
| | Number of technical errors | | | | | |
| | 0 (n=31) | 1 (n=16) | 2 (n=18) | 3 (n=7) | F | p |
| Ball speed (m/sec) | 31.7±2.8 | 31.4±2.7 | 31.9±2.9 | 32.6±2.0 | 0.36 | 0.78 |
| Accuracy* | | | | | | |
| Absolute distance (m) | 0.44±0.10 | 0.38±0.08 | 0.43±0.09 | 0.51±0.08 | 2.42 | 0.07 |
| Horizontal distance (m) | 0.27±0.08 | 0.22±0.08 | 0.23±0.08 | 0.28±0.10 | 1.57 | 0.21 |
| Vertical distance (m) | 0.31±0.09 | 0.28±0.07 | 0.33±0.08 | 0.38±0.09 | 2.45 | 0.07 |
| Quality of pitching (pts) | 26.1±3.1 | 25.6±2.3 | 25.1±2.3 | 26.3±1.6 | 0.63 | 0.60 |

* Accuracy data were missing from 1 pitcher with no error, 2 pitchers with 1 error, 1 pitcher with 2 errors, and 1 pitcher with 3 errors

**TABLE 21**: Effect sizes and statistical power for the comparisons of the performance measures and quality of pitching technique among the pitchers with 0, 1, 2 and 3 errors

| **TABLE 21** | | |
|---|---|---|
| | Effect size† | Power |
| Ball speed (m/sec) | 0.03 | 0.13 |
| Accuracy* | | |
| Absolute distance (m) | 0.06 | 0.73 |
| Horizontal distance (m) | 0.20 | 0.50 |
| Vertical distance (m) | 0.04 | 0.56 |
| Quality of pitching (pts) | 0.11 | 0.18 |

† Eta squared

**TABLE 22**: Comparisons of the shoulder and elbow peak kinetic variables among the pitchers with 0, 1, 2 and 3 errors

| TABLE 22 | | | | | | |
|---|---|---|---|---|---|---|
| | Number of errors | | | | | |
| | 0 (n=31) | 1 (n=16) | 2 (n=18) | 3 (n=7) | F | p |
| Peak elbow proximal force (%BW) | 96.4±12.9 | 95.5±16.6 | 102.0±14.1 | 98.5±16.0 | 0.76 | 0.522 |
| Peak elbow varus moment (%BW*Height) | 3.96±0.82 | 4.20±0.96 | 4.15±0.67 | 3.64±0.47 | 1.03 | 0.386 |
| Peak elbow extension moment (%BW*Height) | 1.74±0.80 | 1.82±0.70 | 1.64±0.56 | 1.80±0.68 | 0.20 | 0.894 |
| Peak shoulder anterior force (%BW) | 33.7±6.45 | 34.3±6.36 | 36.0±6.27 | 31.4±3.12 | 1.08 | 0.366 |
| Peak shoulder proximal force (%BW) | 97.7±14.5 | 95.8±17.1 | 103.2±16.0 | 99.5±17.9 | 0.71 | 0.550 |
| Peak shoulder internal rotation moment (%BW*Height) | 3.88±0.80 | 4.08±0.87 | 4.10±0.73 | 3.53±0.52 | 1.14 | 0.340 |

BW = Body weight

**TABLE 23**: Effect sizes and statistical power for the comparisons of the shoulder and elbow peak kinetic variables among the pitchers with 0, 1, 2 and 3 errors

| TABLE 23 | | |
|---|---|---|
| | Effect size† | Power |
| Peak elbow proximal force (%BW) | 0.09 | 0.20 |
| Peak elbow varus moment (%BW*Height) | 0.08 | 0.27 |
| Peak elbow extension moment (%BW*Height) | 0.01 | 0.09 |
| Peak shoulder anterior force (%BW) | 0.07 | 0.28 |
| Peak shoulder proximal force (%BW) | 0.06 | 0.20 |
| Peak shoulder internal rotation moment (%BW*Height) | 0.07 | 0.29 |

BW = Body weight
† Eta squared

### 4.7 Association between Lateral Lean at Maximal Shoulder External Rotation (LLMER) and a Recent History of Pitching-Related Upper Extremity Injuries

Previous analysis indicated that the pitchers with LLMER pitched at a higher ball speed, and experienced greater joint loading compared to the pitchers who did not demonstrate the error. Since a higher joint loading has been linked to an increased risk of upper extremity injuries, an association between LLMER and a recent self-reported history of pitching-related upper extremity injuries was examined. The self-reported injuries were considered as recent pitching-related upper extremity injuries if they were 1) sustained at the shoulder or elbow joints, 2) sustained from pitching, 3) occurred in the past 2 years, and 4) resulted in more than 7 days lost from baseball participation. We observed that there was no statistically significant association between LLMER and a recent history of injury ($\chi^2$ =3.19, p =0.074) (**TABLE 22**). However, there was a trend that the pitchers with a recent history of injury were more likely to demonstrate LLMER compared to the pitchers without a recent injury history (Relative risk = 1.69, 95%CI = 1.02 - 2.82).

**TABLE 24**: Association between lateral lean at maximal shoulder external rotation (LLMER) and a recent history of pitching-related upper extremity injuries

**TABLE 24**

| | | | LLMER | | Total |
|---|---|---|---|---|---|
| | | | Yes | No | |
| Injury history | Yes | Frequency | 9 | 5 | 14 |
| | | (Expected) | (6.0) | (29.3) | |
| | | (Row %) | (64.3%) | (35.7%) | |
| | No | Frequency | 22 | 36 | 58 |
| | | (Expected) | (25.0) | (33.0) | |
| | | (Row %) | (37.9%) | (62.1%) | |
| Total | | | 31 | 41 | 72 |

$\chi^2$ =3.19, p =0.074

### 4.8 Comparisons of the Kinematic Variables between the Pitchers with and without Lateral Lean at Maximal Shoulder External Rotation

In order to understand how the pitching kinematics differ between pitchers with and without LLMER, the upper extremity and upper torso kinematic variables were compared between the pitchers with and without LLMER (**Table 23**). There were no significant differences in the shoulder or elbow joint angles, peak joint angular velocity, or temporal variables between pitchers with and without LLMER ($p>0.05$). On the other hand, the pitchers with LLMER demonstrated less upper torso flexion at stride foot contact (**Figure 22**), and less upper torso rotation (**Figure 23**) and greater upper torso lateral flexion (**Figure 24**) at maximal shoulder external rotation and ball release.

**TABLE 25**: Comparisons of the kinematic variables between the pitchers with and without lateral lean at maximal shoulder external rotation (LLMER)

| **TABLE 25** | LLMER | | | |
|---|---|---|---|---|
| | Yes (n=31) | No (n=41) | t | p |
| Stride foot contact | | | | |
| Pelvis rotation angle (°) | 17.5±11.2 | 14.5±11.8 | -1.08 | 0.283 |
| Upper torso rotation angle (°) | -11.3±9.7 | -11.7±9.7 | -0.15 | 0.881 |
| Upper torso lateral flexion angle (°) | 6.5±7.6 | 7.0±7.8 | 0.27 | 0.786 |
| Upper torso forward flexion angle (°) | -0.72±9.4 | 7.0±8.5 | 3.67 | <0.001 |
| Maximal shoulder external rotation | | | | |
| Upper torso rotation angle (°) | 88.1±8.8 | 95.6±11.0 | 3.09 | 0.003 |
| Upper torso lateral flexion angle (°) | -34.6±11.2 | -21.9±8.0 | 5.65 | <0.001 |
| Upper torso forward flexion angle (°) | 20.0±7.3 | 19.3±9.4 | -0.33 | 0.742 |
| Shoulder external rotation angle (°) | 177.9±9.1 | 173.5±11.6 | -1.74 | 0.086 |
| Shoulder horizontal abduction angle (°) | 6.8±8.4 | 6.8±11.1 | -0.01 | 0.996 |
| Shoulder elevation angle (°) | 94.9±6.5 | 95.4±8.2 | 0.28 | 0.778 |
| Elbow extension angle (°) | 115.2±15.0 | 117.4±13.1 | 0.67 | 0.507 |
| Ball release | | | | |
| Upper torso rotation angle (°) | 92.8±13.6 | 105.7±13.2 | 4.08 | <0.001 |
| Upper torso lateral flexion angle (°) | -30.3±14.2 | -17.5±10.2 | 4.46 | <0.001 |
| Upper torso forward flexion angle (°) | 33.6±10.3 | 34.9±9.7 | 0.58 | 0.561 |
| Shoulder horizontal abduction angle (°) | 1.2±8.4 | 1.6±9.8 | -0.49 | 0.629 |
| Shoulder elevation angle (°) | 97.3±6.7 | 97.4±8.1 | 0.06 | 0.953 |
| Elbow extension angle (°) | 165.5±5.3 | 164.9±4.7 | -0.49 | 0.629 |
| Peak velocity | | | | |
| Upper torso rotation velocity (°/sec) | 887.8±115.3 | 889.3±100.1 | 0.06 | 0.953 |
| Shoulder horizontal adduction velocity (°/sec) | 454.6 ±140.0 | 444.2±116.5 | -0.35 | 0.730 |
| Shoulder internal rotation velocity (°/sec) | 6777.0±1339.4 | 6437.2±1086.1 | -1.19 | 0.239 |
| Elbow extension velocity (°/sec) | 2013.9±208.8 | 1927.6±208.7 | -1.74 | 0.087 |
| Temporal variables | | | | |
| Initiation of upper torso rotation (%) | 14.3±13.6 | 20.0±15.0 | 1.64 | 0.105 |
| Maximal shoulder external rotation (%) | 82.2±4.7 | 83.2±3.2 | 1.15 | 0.254 |

**TABLE 26**: Effect sizes and statistical power for the comparisons of the kinematic variables between the pitchers with and without lateral lean at maximal shoulder external rotation (LLMER)

| **TABLE 26** | | |
|---|---|---|
| | Effect size† | Power |
| Stride foot contact | | |
| Pelvis rotation angle (°) | 0.26 | 0.19 |
| Upper torso rotation angle (°) | 0.04 | 0.05 |
| Upper torso lateral flexion angle (°) | -0.07 | 0.06 |
| Upper torso forward flexion angle (°) | -0.80 | 0.91 |
| Maximal shoulder external rotation | | |
| Upper torso rotation angle (°) | -0.71 | 0.83 |
| Upper torso lateral flexion angle (°) | -1.12 | 0.99 |
| Upper torso forward flexion angle (°) | 0.08 | 0.06 |
| Shoulder external rotation angle (°) | 0.41 | 0.39 |
| Shoulder horizontal abduction angle (°) | 0.00 | 0.05 |
| Shoulder elevation angle (°) | -0.07 | 0.06 |
| Elbow extension angle (°) | -0.16 | 0.10 |
| Ball release | | |
| Upper torso rotation angle (°) | -0.88 | 0.96 |
| Upper torso lateral flexion angle (°) | -0.95 | 0.98 |
| Upper torso forward flexion angle (°) | -0.13 | 0.09 |
| Shoulder horizontal abduction angle (°) | -0.04 | 0.05 |
| Shoulder elevation angle (°) | -0.01 | 0.05 |
| Elbow extension angle (°) | 0.12 | 0.08 |
| Peak velocity | | |
| Upper torso rotation velocity (°/sec) | -0.01 | 0.05 |
| Shoulder horizontal adduction velocity (°/sec) | 0.08 | 0.06 |
| Shoulder internal rotation velocity (°/sec) | 0.28 | 0.22 |
| Elbow extension velocity (°/sec) | 0.41 | 0.40 |
| Temporal variables | | |
| Initiation of upper torso rotation (%) | -0.39 | 0.37 |
| Maximal shoulder external rotation (%) | -0.26 | 0.19 |

† Cohen's d effect size

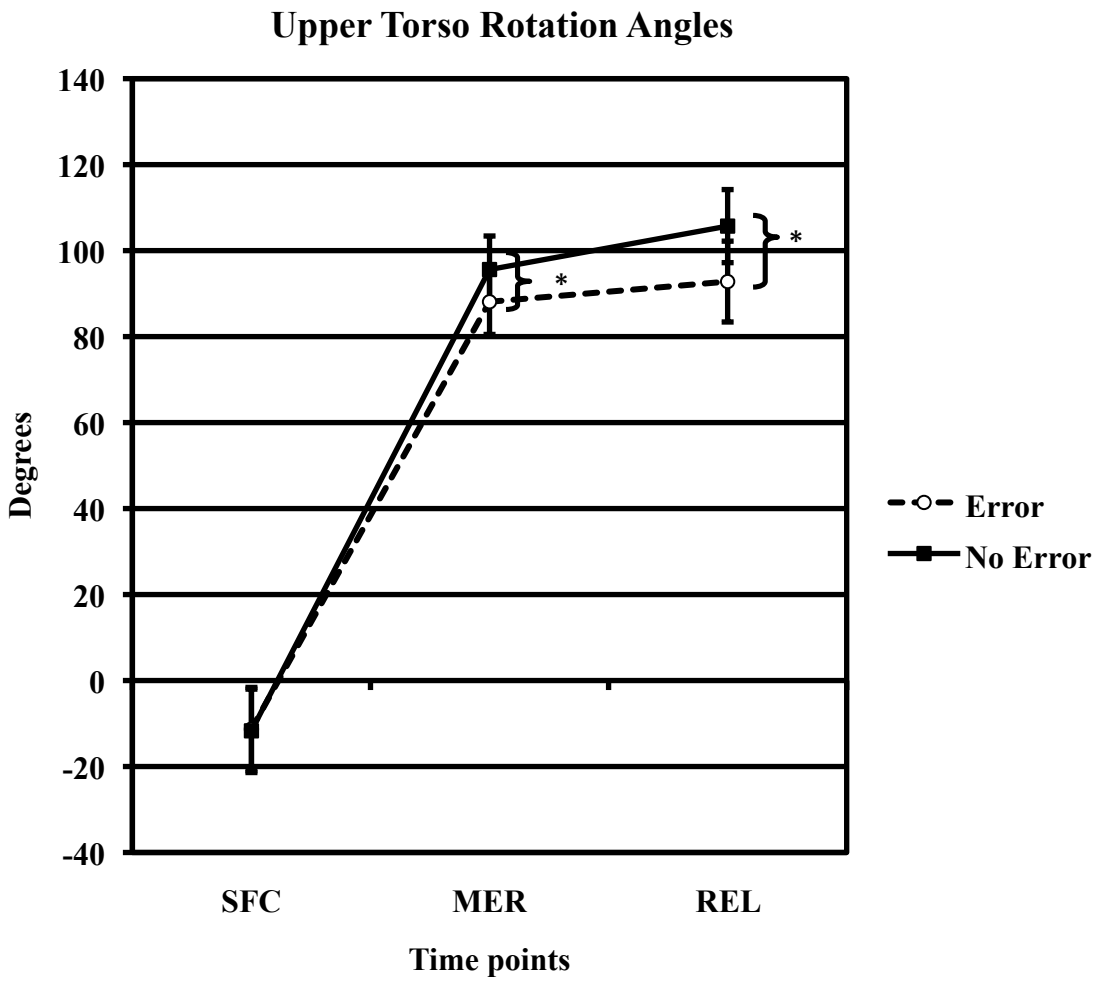



**Figure 22.** Upper torso rotation angles between the pitchers with and without LLMER. The pitchers with LLMER demonstrated a lower rotation angle compared to the pitchers without LLMER at maximal shoulder external rotation and ball release. (*) Indicates statistical significant at an $\alpha$ level of 0.05.

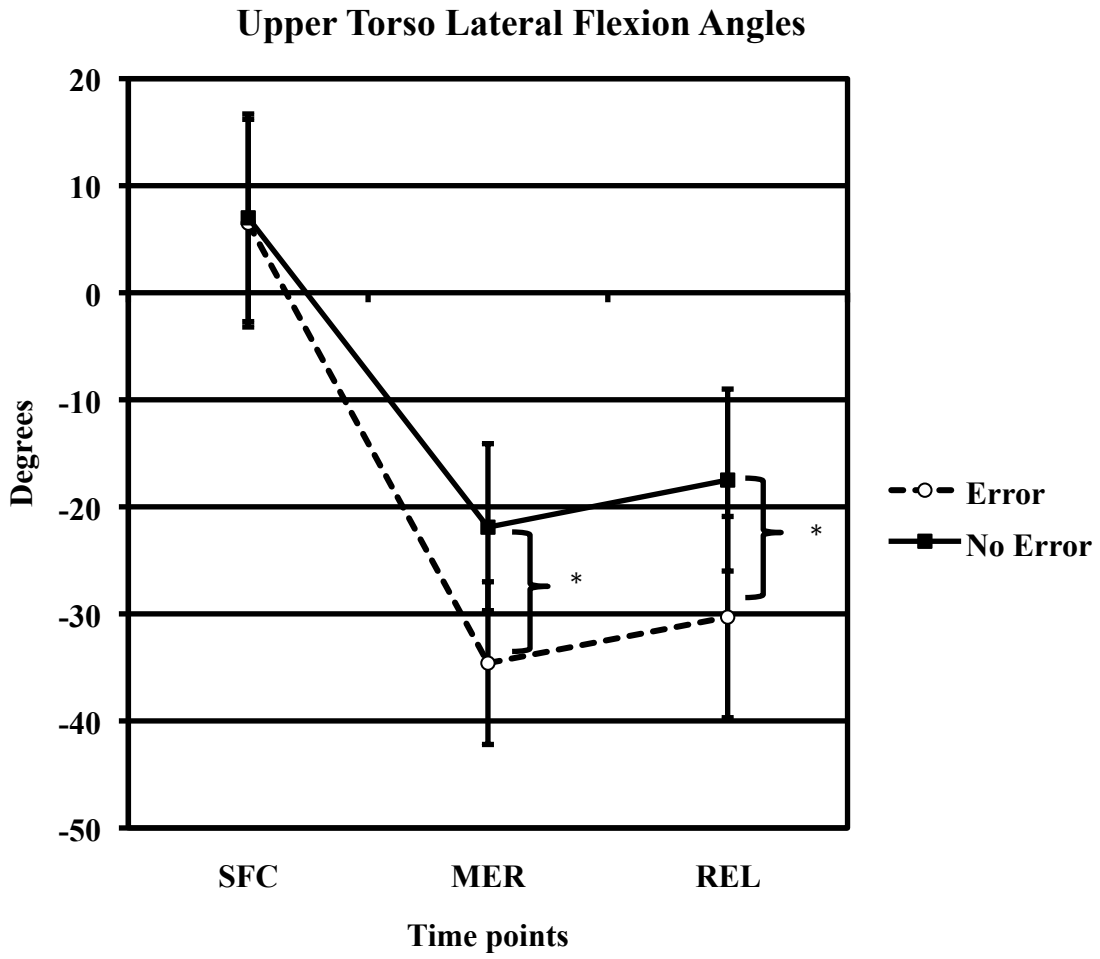



**Figure 23.** Upper torso lateral flexion angles between the pitchers with and without LLMER. The pitchers with LLMER demonstrated a greater upper torso lateral flexion towards the non-throwing shoulder compared to the pitchers without LLMER at maximal shoulder external rotation and ball release. (*) Indicates statistical significant at an $\alpha$ level of 0.05.

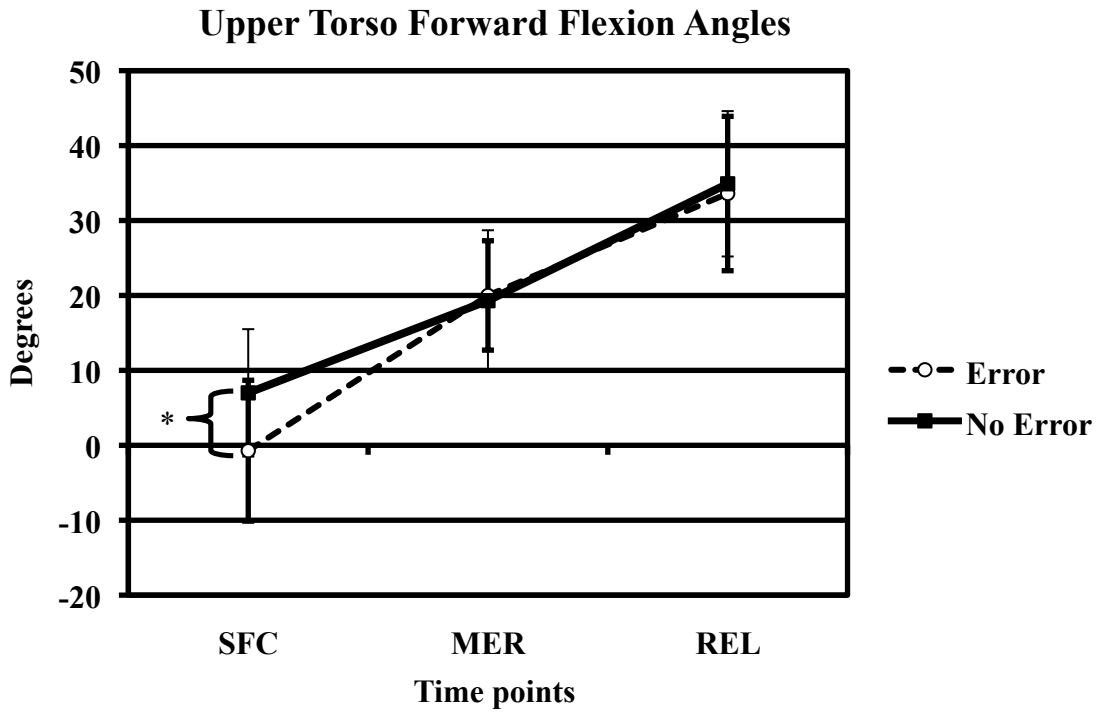



**Figure 24.** Upper torso forward flexion angles between the pitchers with and without LLMER. The pitchers with LLMER demonstrated a more extended upper torso compared to the pitchers without LLMER at stride foot contact. (*) Indicates statistical significant at an α level of 0.05.

### 4.9 Effects of the Technical Errors at Stride Foot Contact and Stride Offset on Lateral Lean at Maximal Shoulder External Rotation (LLMER)

In pitching, the instant of stride foot contact precedes the instant of maximal shoulder external rotation. Therefore, we examined the effects of technical errors at stride foot contact (OS, BLSFC, and LLSFC) on the LLMER. In addition, as we reviewed the videos from the pitching trials, we noticed that the pitchers who appeared to have an excessively closed stance offset (i.e. stride foot landed more than 10cm inside of the line connecting the stance leg and the home base) tended to demonstrate LLMER more often than the pitchers who took strides straight towards the target. Therefore, we examined an association between the stance

offset (closed stance) and LLMER to test our observation. Coincidentally, one of the items in the qualitative pitching evaluation form pertained to the stride offset (normal vs. excessively closed, vs. excessively open). The ratings for this item was used to determine whether or not the pitchers demonstrated an excessively closed stride offset. The statistical significance of the associations were assessed using the Chi-square statistics of association.

There was a strong association between BLSFC and LLMER ($\chi^2$=36.6, p<0.001) (**Table 24**). We observed that all pitchers (20 out of 20) who demonstrated BLSFC proceeded to demonstrate LLMER, whereas only 21.2% (11 out of 52) of the pitchers who did not demonstrate BLSFC demonstrated LLMER. The other errors at stride foot contact (OS and LLSFC) were not associated with LLMER (**Tables 25 & 26**). Additionally, there was a strong association between the excessively closed stance offset and LLMER ($\chi^2$=14.0, p<0.001) (**Table 27**). We observed that 82% of the pitchers (14 out of 17) with an excessively closed stance offset proceeded to demonstrate LLMER, whereas only 30.9% (17 out of 55) of the pitchers who did not have an excessively closed stance demonstrated LLMER.

**TABLE 27**: Association between backward lean at stride foot contact (BLSFC) and lateral lean at maximal shoulder external rotation (LLMER)

| **TABLE 27** | | | LLMER | | Total |
|---|---|---|---|---|---|
| | | | Yes | No | |
| BLSFC | Yes | Frequency<br>(Expected)<br>(Row %) | 20<br>(8.6)<br>(100.0%) | 0<br>(11.4)<br>(0.0%) | 20 |
| | No | Frequency<br>(Expected)<br>(Row %) | 11<br>(22.4)<br>(21.2%) | 41<br>(29.6)<br>(78.8%) | 52 |
| Total | | | 31 | 41 | 72 |

$\chi^2$ =36.6, p <0.001

**TABLE 28**: Association between open shoulder at stride foot contact (OS) and lateral lean at maximal shoulder external rotation (LLMER)

| **TABLE 28** | | | LLMER | | Total |
|---|---|---|---|---|---|
| | | | Yes | No | |
| OS | Yes | Frequency<br>(Expected)<br>(Row %) | 1<br>(1.72)<br>(25.0%) | 3<br>(2.3)<br>(75.0%) | 4 |
| | No | Frequency<br>(Expected)<br>(Row %) | 30<br>(29.3)<br>(21.2%) | 38<br>(38.7)<br>(78.8%) | 68 |
| Total | | | 31 | 41 | 72 |

$\chi^2$ =0.56, p =0.453

**TABLE 29**: Association between lateral lean at stride foot contact (LLSFC) and lateral lean at maximal shoulder external rotation (LLMER)

| TABLE 29 | | | LLMER | | Total |
|---|---|---|---|---|---|
| | | | Yes | No | |
| LLSFC | Yes | Frequency<br>(Expected)<br>(Row %) | 8<br>(5.6)<br>(61.5%) | 5<br>(7.4)<br>(38.5%) | 13 |
| | No | Frequency<br>(Expected)<br>(Row %) | 23<br>(25.4)<br>(39.0%) | 36<br>(33.6)<br>(61.0%) | 59 |
| Total | | | 31 | 41 | 72 |

$\chi^2$ =2.21, p =0.137

**TABLE 30**: Association between excessive closed stance offset and lateral lean at maximal shoulder external rotation (LLMER)

| TABLE 30 | | | LLMER | | Total |
|---|---|---|---|---|---|
| | | | Yes | No | |
| Closed Stance | Yes | Frequency<br>(Expected)<br>(Row %) | 14<br>(7.3)<br>(82.4%) | 3<br>(9.7)<br>(17.7%) | 17 |
| | No | Frequency<br>(Expected)<br>(Row %) | 17<br>(23.7)<br>(30.9%) | 38<br>(31.3)<br>(69.1%) | 55 |
| Total | | | 31 | 41 | 72 |

$\chi^2$ =14.0, p <0.001

### 4.10 Relationships between the Trunk Kinematics at Stride Foot Contact and Maximal Shoulder External Rotation

In order to supplement the previous analysis that demonstrated the associations between the technical errors at stride foot contact and LLMER, the relationships between upper torso kinematics (rotation, lateral flexion, and forward flexion) at stride foot contact and the lateral flexion angle at maximal shoulder external rotation were assessed using the

Pearson correlation coefficients (**Table 28**). We observed that the upper torso flexion angle at stride foot contact was moderately correlated with the lateral flexion angle at the maximal shoulder external rotation ($r = 0.619$, $p < 0.001$). This correlation indicates that the pitchers who have a greater upper torso flexion angle (sagittal plane) at stride foot contact are likely to have less lateral trunk flexion towards the non-throwing shoulder at maximal shoulder external rotation. The upper torso rotation and lateral flexion angles at the stride foot contact were not correlated with the lateral flexion angle at the maximal shoulder external rotation ($p < 0.05$).

**TABLE 31:** Correlations between the upper torso kinematics at stride foot contact (SFC) and upper torso lateral flexion angle at maximal shoulder external rotation

| **TABLE 31** | | |
|---|---|---|
| | r | p |
| Upper torso rotation angle at SFC (°) | 0.044 | 0.713 |
| Upper torso lateral flexion angle at SFC (°) | 0.042 | 0.722 |
| Upper torso forward flexion angle at SFC (°) | 0.619 | <0.001 |

### 4.11 Effects of the Forward Trunk Tilt Angle at Ball Release on the Performance Measures and Joint Loading

We observed that the pitchers with FT pitched with a lower ball velocity and lower proximal forces at the shoulder and elbow joints. However, since only 5 pitchers demonstrated FT, we followed up this observation by comparing the ball speed and joint loading among the pitchers who demonstrated 1) inadequate (< 25°), 2) normal (25-35°), 3) high (35-45°), and 4) excessive (> 45°) forward trunk tilt (FTT) angles at ball release. The FTT angle was calculated as the angle of the long (vertical) axis of the upper torso projected onto the global X-Y plane (**Figure 20**). This angle represents the angle coaches and parents

can visualize using video cameras. The classification of the trunk flexion angles (inadequate, normal, high, and excessive) was based on the previous literature, which stated that pitcher's trunk should be approximately 30° at ball release.[76] The pitchers with FTT angle that was within 5° of 30° (25-35°) were considered to have normal FTT angle, and pitchers with FTT angle that was lower than 25° were considered to have inadequate FTT. The pitchers with FTT angle that was greater than 25° were divided into high (25-35°) and excessive (35-45°) FTT groups. Based on this classification, there were 11, 16, 23, and 22 pitchers with inadequate, normal, high, and excessive FTT angles at ball release, respectively. One way ANOVA models and Bonferroni post hoc tests were used to examine whether the joint loading, performance measures, and quality of pitching technique in the pitchers with inadequate, high, and excessive FTT angles differed from that in the pitchers with normal FTT angle. An adjusted alpha level of 0.017 (= 0.05/3) was used to determine the statistical significance for post hoc analyses.

We observed that there were significant differences in ball speed ($F_{3,68} = 3.39$, $p = 0.023$) and accuracy in the horizontal direction ($F_{3,68} = 3.04$, $p = 0.035$) among the groups (**Table 29**). The pitchers with an inadequate FTT angle pitched with a lower ball velocity compared to the pitchers with a normal FTT angle ($t = 2.76$, $p = 0.007$). The pitchers with a high FTT angle had a significantly better accuracy in the horizontal direction compared to the pitchers with a normal FTT angle ($t = 2.99$, $p=0.004$).

We also observed that there were significant differences in the peak elbow proximal force ($F_{3,68} = 5.18$, $p = 0.003$) and peak shoulder proximal force ($F_{3,68} = 5.44$, $p = 0.002$) among the pitchers with inadequate, normal, high, and excessive FTT angles (**Table 30**). Based on the post-hoc analyses, pitchers with inadequate FTT experienced a significantly

lower peak shoulder proximal force compared to the pitchers with normal FTT angle (t = 2.54, p = 0.013). However, the peak elbow proximal force in the pitchers with inadequate, high, and excessive FTT was not significantly different from that in the pitchers with normal FTT angle (p > 0.017).

Although statistically insignificant, we observed that there was a trend that the peak elbow extension moment was different among the pitchers with insufficient, normal, high, and excessive FTT angles at ball release ($F_{3,67}$ = 2.47, p = 0.069) (**Figure 25**). The observations of the group means indicated that the peak elbow extension moment in the pitchers with insufficient (<25°) FTT angle (2.26±0.64, 95%CI = 1.82-2.69) tended to be greater than the peak elbow extension moment in the pitchers with normal (1.67±0.57, 95%CI = 1.37-1.98), high (1.64±0.84, 95%CI = 1.27-2.00), and excessive (1.64±0.59, 95%CI = 1.38-1.90) FTT angles. There were no significant differences in the other variables (p > 0.05).

**TABLE 32**: Comparisons of the performance measures and the quality of pitching technique among the pitchers with insufficient (<25°), normal (25-35°), high (35-45°), and excessive (>45°) forward trunk tilt angles at ball release

**TABLE 32**

| | Forward Trunk Tilt Angle at Ball Release | | | | | |
|---|---|---|---|---|---|---|
| | Inadequate (n=11) | Normal (n=16) | High (n=23) | Excessive (n=22) | F | p |
| Ball speed (m/sec) | 29.5±2.7 | 32.3±2.4 | 31.9±2.7 | 32.3±2.5 | 3.39 | 0.023 |
| Accuracy * | | | | | | |
| Absolute distance (m) | 0.47±0.10 | 0.44±0.09 | 0.39±0.10 | 0.45±0.09 | 2.10 | 0.109 |
| Horizontal distance (m) | 0.25±0.07 | 0.29±0.08 | 0.21±0.09 | 0.25±0.08 | 3.04 | 0.035 |
| Vertical distance (m) | 0.35±0.09 | 0.29±0.08 | 0.29±0.08 | 0.34±0.09 | 1.87 | 0.144 |
| Quality of pitching (pts) | 24.4±3.0 | 26.7±1.5 | 25.6±2.6 | 26.0±2.9 | 1.70 | 0.176 |

* Accuracy data were missing from 1 pitcher with normal forward trunk tilt, 2 pitchers with high forward trunk tilt, and 2 pitcher with excessive forward trunk tilt

**TABLE 33**: Effect sizes and statistical power for the comparisons of the performance measures and the quality of pitching technique among the pitchers with insufficient (<25°), normal (25-35°), high (35-45°), and excessive (>45°) forward trunk tilt angles at ball release

| **TABLE 33** | Effect size† | Power |
|---|---|---|
| Ball speed (m/sec) | 0.36 | 0.696 |
| Accuracy * | | |
| Absolute distance (m) | 0.30 | 0.581 |
| Horizontal distance (m) | 0.36 | 0.699 |
| Vertical distance (m) | 0.29 | 0.536 |
| Quality of pitching (pts) | 0.26 | 0.437 |

† Eta squared

**TABLE 34**: Comparisons of the shoulder and elbow peak kinetic variables among the pitchers with insufficient (<25°), normal (25-35°), high (35-45°), and excessive (>45°) forward trunk tilt angles at ball release

| **TABLE 34** | Forward Trunk Tilt Angle at Ball Release | | | | | |
|---|---|---|---|---|---|---|
| | Inadequate (n=11) | Normal (n=16) | High (n=23) | Excessive (n=22) | F | p |
| Peak elbow proximal force (%BW) | 84.8±15.2 | 95.7±15.2 | 100.1±11.4 | 103.3±12.3 | 5.18 | 0.003 |
| Peak elbow varus moment (%BW*Height) | 3.72±0.73 | 3.94±0.95 | 4.05±0.68 | 4.23±0.81 | 1.15 | 0.334 |
| Peak elbow extension moment (%BW*Height) | 2.25±0.64 | 1.68±0.57 | 1.64±0.84 | 1.64±0.59 | 2.47 | 0.069 |
| Peak shoulder anterior force (%BW) | 31.9±6.2 | 35.3±7.7 | 34.5±4.7 | 34.2±6.4 | 0.71 | 0.548 |
| Peak shoulder proximal force (%BW) | 83.7±16.9 | 98.0±16.5 | 101.1±12.3 | 104.6±13.6 | 5.44 | 0.002 |
| Peak shoulder internal rotation moment (%BW*Height) | 3.55±0.70 | 3.86±0.94 | 4.00±0.66 | 4.14±0.77 | 1.55 | 0.211 |

BW = Body weight

**TABLE 35**: Effect sizes and statistical power for the comparisons of the shoulder and elbow peak kinetic variables among the pitchers with insufficient (<25°), normal (25-35°), high (35-45°), and excessive (>45°) forward trunk tilt angles at ball release

| **TABLE 35** | | |
|---|---|---|
| | Effect size† | Power |
| Peak elbow proximal force (%BW) | 0.43 | 0.86 |
| Peak elbow varus moment (%BW*Height) | 0.22 | 0.28 |
| Peak elbow extension moment (%BW*Height) | 0.31 | 0.55 |
| Peak shoulder anterior force (%BW) | 0.18 | 0.19 |
| Peak shoulder proximal force (%BW) | 0.44 | 0.87 |
| Peak shoulder internal rotation moment (%BW*Height) | 0.25 | 0.38 |

BW = Body weight
† Eta Squared

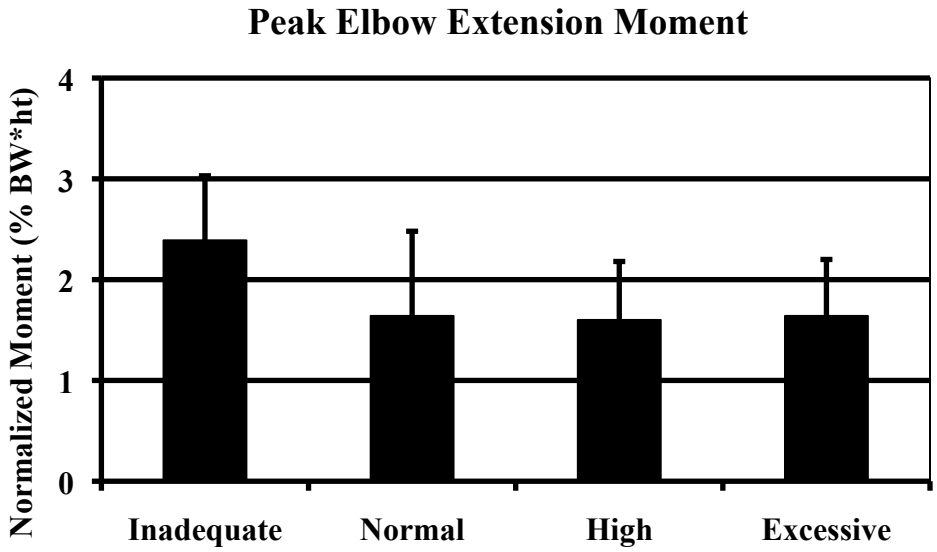



**Figure 25.** Differences in the peak elbow extension moments between the pitchers with inadequate (<25°), normal (25-35°), high (35-45°), and excessive (>45°) forward trunk tilt angle at ball release.

### 4.12 Comparison of the Kinematic Variables among the Pitchers with Inadequate, Normal, High, and Excessive Forward Trunk Tilt

In order to understand how the upper extremity and trunk kinematics differ among the pitchers with inadequate, normal, high, and excessive FTT angles, the kinematic variables were compared across the groups using ANOVA models and Bonferroni post hoc tests. An adjusted alpha level of 0.017 (= 0.05/3) was used to determine the statistical significance for the post hoc analyses.

The omnibus ANOVA was significant for the maximal shoulder external rotation angle, and the upper torso rotation, upper torso flexion, and shoulder elevation angles at the maximal shoulder external rotation and ball release (**Table 31**). There were no between group differences in the other variables (**Tables 31 & 32**). Based on the post hoc analyses, we observed that the pitchers with excessive FTT demonstrated a greater maximal shoulder external rotation ( $t = 4.29$, $p < 0.001$) and upper torso rotation at the maximal shoulder external rotation ( $t = 4.47$, $p < 0.001$) and at ball release ( $t = 4.49$, $p < 0.001$) compared to the pitchers with normal FTT (**Figure 26**). The pitchers with high FTT also demonstrated a greater upper torso rotation at the maximal shoulder external rotation compared to the pitchers with normal FTT ( $t = 2.96$, $p = 0.001$) (**Figure 26**). Additionally, we observed that the pitchers with inadequate FTT angle demonstrated less upper torso flexion at the maximal shoulder external rotation ( $t = 3.98$, $p < 0.001$) and at ball release ( $t = 3.34$, $p = 0.001$) than the pitchers with a normal FTT angle (**Figure 27**). The upper torso lateral flexion angles at stride foot contact, maximal shoulder external rotation, and ball release are presented in **Figure 28**. The post hoc tests were statistically insignificant at an adjusted alpha level of 0.0167 for the rest of the variables.

**TABLE 36**: Comparisons of the joint/segment angles among the pitchers with inadequate (<25°), normal (25-35°), high (35-45°), and excessive (>45°) forward trunk tilt

| **TABLE 36** | Forward Trunk Tilt at Ball Release | | | | | |
|---|---|---|---|---|---|---|
| | Inadequate (<25°) (n=11) | Normal (25-35°) (n=16) | High (25-35°) (n=23) | Excessive (25-35°) (n=22) | F | p |
| Stride foot contact | | | | | | |
| Pelvis rotation angle (°) | 10.8±6.7 | 17.1±14.4 | 16.0±11.2 | 17.1±11.7 | 0.85 | 0.469 |
| Upper torso rotation angle (°) | -9.7±7.5 | -8.4±9.8 | -11.0±9.8 | -15.4±9.6 | 1.97 | 0.127 |
| Upper torso lateral tilt angle (°) | 8.6±6.9 | 9.3±7.7 | 5.8±7.3 | 5.2±8.3 | 1.22 | 0.309 |
| Upper torso flexion angle (°) | 6.3±7.6 | 3.9±11.5 | 3.8±8.7 | 2.2±10.4 | 0.44 | 0.723 |
| Maximal shoulder external rotation | | | | | | |
| Upper torso rotation angle (°) | 98.6±12.5 | 99.6±8.5 | 90.6±8.8 | 85.9±8.6 | 8.62 | <0.001 |
| Upper torso lateral tilt angle (°) | -25.4±7.1 | -24.8±9.3 | -25.7±10.1 | -31.9±14.6 | 1.77 | 0.162 |
| Upper torso flexion angle (°) | 8.6±7.4 | 19.6±6.7 | 20.7±6.6 | 23.9±7.7 | 11.7 | <0.001 |
| Shoulder external rotation angle (°) | 163.9±8.3 | 171.3±6.3 | 176.1±10.6 | 183.4±7.8 | 14.1 | <0.001 |
| Shoulder horizontal abduction angle (°) | 8.5±14.7 | 4.1±9.0 | 8.5±9.6 | 6.3±8.2 | 0.73 | 0.539 |
| Shoulder elevation angle (°) | 88.9±7.2 | 94.7±8.1 | 96.1±5.6 | 97.6±7.4 | 3.97 | 0.011 |
| Elbow extension angle (°) | 119.4±15.3 | 119.6±14.4 | 112.7±12.7 | 116.8±14.0 | 1.00 | 0.399 |
| Ball release | | | | | | |
| Upper torso rotation angle (°) | 109.0±11.4 | 108.4±8.7 | 100.2±13.4 | 89.6±14.9 | 9.01 | <0.001 |
| Upper torso lateral tilt angle (°) | -23.1±9.9 | -19.3±10.0 | -20.8±12.4 | -27.9±17.4 | 1.60 | 0.197 |
| Upper torso flexion angle (°) | 23.2±6.8 | 34.8±5.9 | 36.5±7.7 | 37.3±12.0 | 7.08 | <0.001 |
| Shoulder horizontal abduction angle (°) | 3.0±12.7 | -1.1±7.6 | 2.9±10.1 | 0.95±7.1 | 0.72 | 0.546 |
| Shoulder elevation angle (°) | 91.3±8.7 | 97.3±8.1 | 97.9±6.1 | 100.1±6.5 | 3.72 | 0.015 |
| Elbow extension angle (°) | 163.5±5.8 | 168.0±4.7 | 164.1±4.1 | 165.1±4.9 | 2.27 | 0.051 |

**TABLE 37**: Effect sizes and statistical power for the comparison of the joint/segment angles among the pitchers with inadequate (<25°), normal (25-35°), high (35-45°), and excessive (>45°) forward trunk tilt

| **TABLE 37** | | |
|---|---|---|
| | Effect size[†] | Power |
| Stride foot contact | | |
| Pelvis rotation angle (°) | 0.01 | 0.22 |
| Upper torso rotation angle (°) | 0.01 | 0.45 |
| Upper torso lateral tilt angle (°) | 0.23 | 0.32 |
| Upper torso flexion angle (°) | 0.14 | 0.08 |
| Maximal shoulder external rotation | | |
| Upper torso rotation angle (°) | 0.52 | 0.97 |
| Upper torso lateral tilt angle (°) | 0.27 | 0.43 |
| Upper torso flexion angle (°) | 0.58 | 0.99 |
| Shoulder external rotation angle (°) | 0.62 | 0.99 |
| Shoulder horizontal abduction angle (°) | 0.18 | 0.20 |
| Shoulder elevation angle (°) | 0.39 | 0.68 |
| Elbow extension angle (°) | 0.21 | 0.26 |
| Ball release | | |
| Upper torso rotation angle (°) | 0.53 | 0.97 |
| Upper torso lateral tilt angle (°) | 0.26 | 0.99 |
| Upper torso flexion angle (°) | 0.49 | 0.94 |
| Shoulder horizontal abduction angle (°) | 0.18 | 0.20 |
| Shoulder elevation angle (°) | 0.38 | 0.74 |
| Elbow extension angle (°) | 0.33 | 0.61 |

[†] Eta squared

**TABLE 38**: Comparison of the peak joint velocity and temporal variables among the pitchers with inadequate (<25°), normal (25-35°), high (35-45°), and excessive (>45°) forward trunk tilt

**TABLE 38**

| | Forward Trunk Tilt at Ball Release | | | | | |
|---|---|---|---|---|---|---|
| | Inadequate (<25°) (n=11) | Normal (25-35°) (n=16) | High (25-35°) (n=23) | Excessive (25-35°) (n=22) | F | p |
| Peak velocity | | | | | | |
| Upper torso rotation velocity (°/sec) | 897.7±98.9 | 902.9±113.0 | 897.7±114.5 | 864.3±98.1 | 0.55 | 0.647 |
| Shoulder horizontal adduction velocity (°/sec) | 464.9±122.1 | 448.3±111.7 | 463.2±144.0 | 425.6±123.7 | 0.40 | 0.756 |
| Shoulder internal rotation velocity (°/sec) | 6383.1±1776.2 | 7161.4±975.6 | 6257.2±1126.5 | 6604.6±1001.3 | 1.97 | 0.127 |
| Elbow extension velocity (°/sec) | 1918.5±281.3 | 2039.7±148.7 | 1945.8±216.9 | 1953.2±207.0 | 0.92 | 0.434 |
| Temporal variables | | | | | | |
| Initiation of upper torso rotation (%) | 23.4±13.3 | 17.9±15.8 | 16.4±17.4 | 15.5±10.8 | 0.77 | 0.516 |
| Maximal shoulder external rotation (%) | 82.4±3.6 | 84.0±4.8 | 81.6±3.5 | 83.2±3.7 | 1.29 | 0.286 |

**TABLE 39**: Effect sizes and statistical power for the comparison of the peak joint velocity and temporal variables among the pitchers with inadequate (<25°), normal (25-35°), high (35-45°), and excessive (>45°) forward trunk tilt

| **TABLE 39** | | |
|---|---|---|
| | Effect size[†] | Power |
| Peak velocity | | |
| Upper torso rotation velocity (°/sec) | 0.15 | 0.73 |
| Shoulder horizontal adduction velocity (°/sec) | 0.13 | 0.13 |
| Shoulder internal rotation velocity (°/sec) | 0.28 | 0.47 |
| Elbow extension velocity (°/sec) | 0.20 | 0.25 |
| Temporal variables | | |
| Initiation of upper torso rotation (%) | 0.18 | 0.21 |
| Maximal shoulder external rotation (%) | 0.24 | 0.34 |

[†] Eta squared

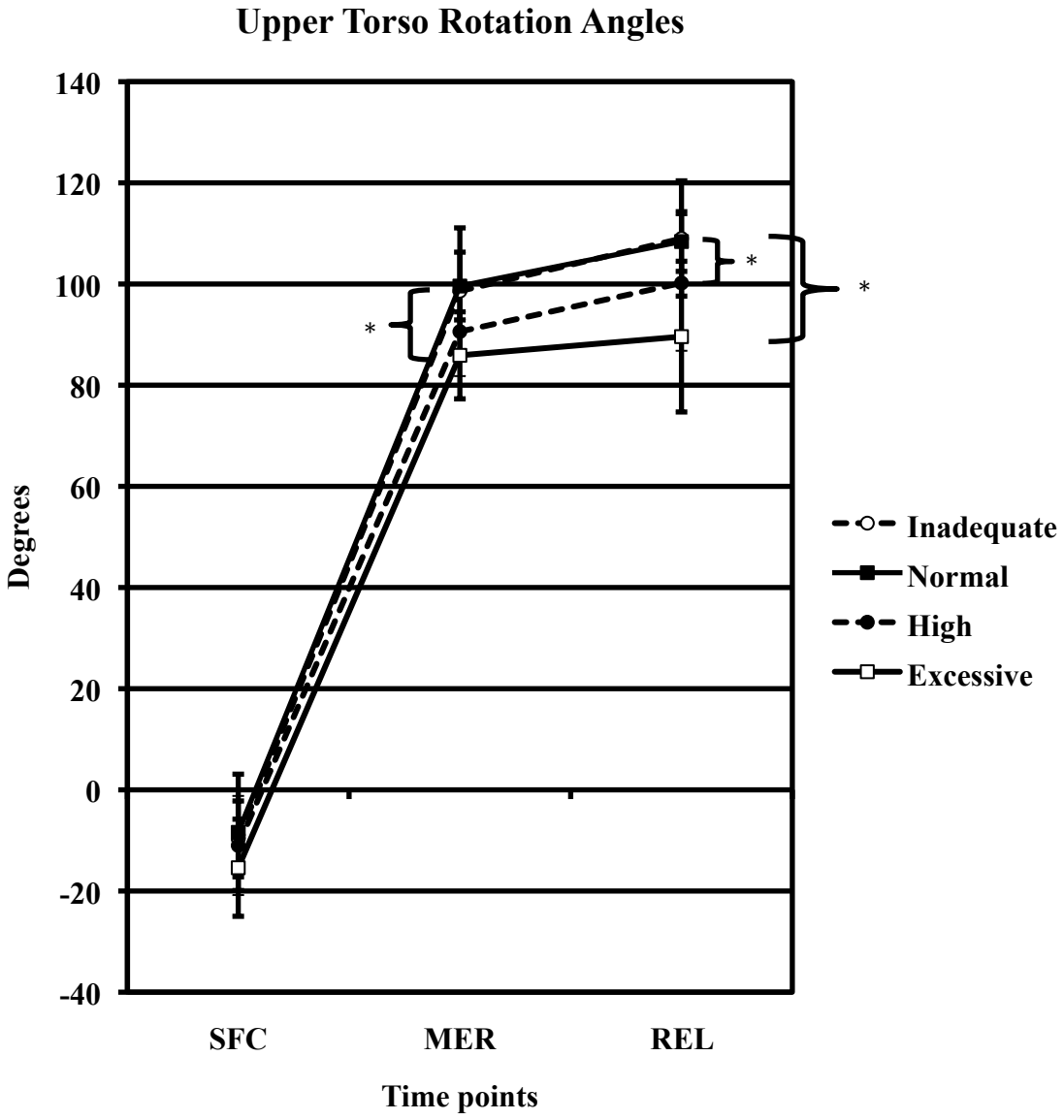



**Figure 26.** Upper torso rotation angles in pitchers with inadequate, normal, high, and excessive forward trunk tilt (FTT) angle at ball release. The pitchers with high FT angle demonstrated a greater upper torso rotation relative to the pitchers with a normal forward FT angle at ball release. The pitchers with excessive FT angle demonstrated a greater upper torso rotation relative to the pitchers with normal FT angle at maximal shoulder external rotation and at ball release.

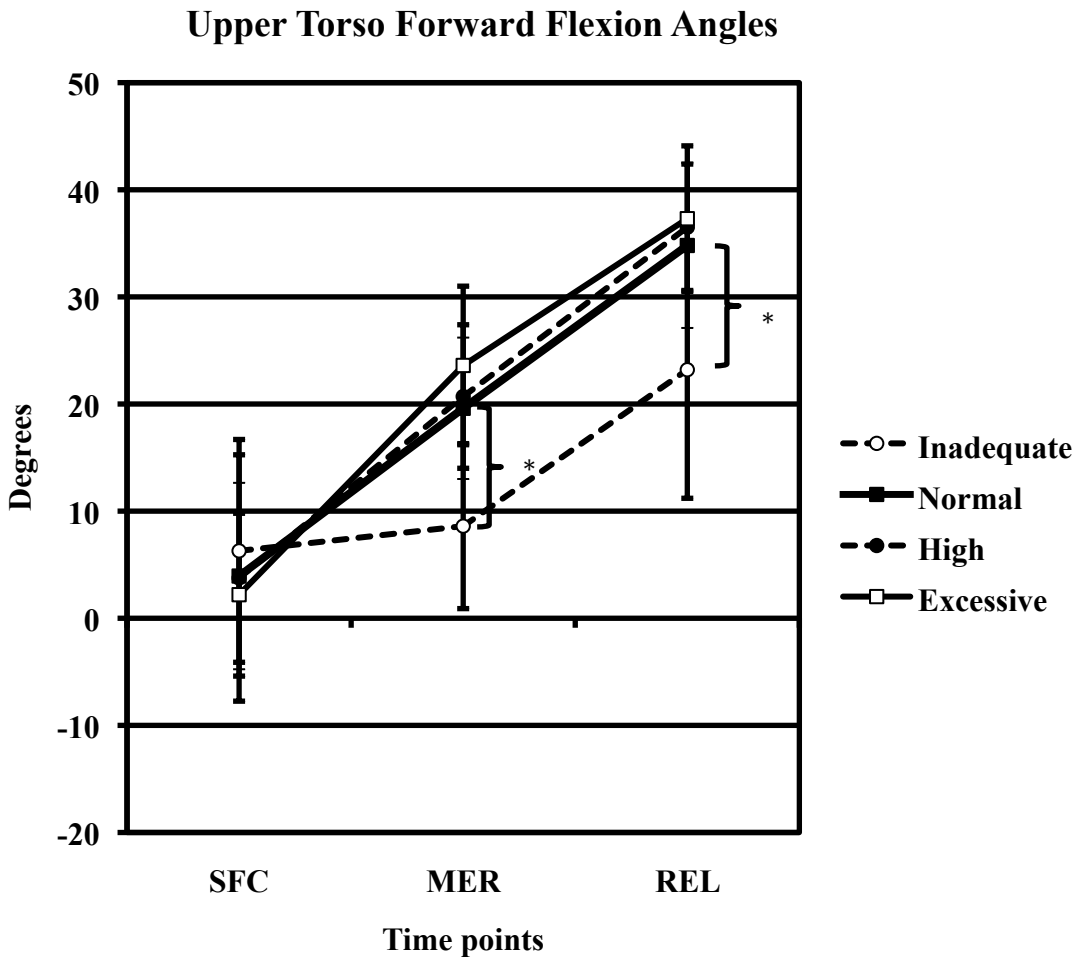



**Figure 27.** Upper torso flexion angles in pitchers with inadequate, normal, high, and excessive forward trunk tilt (FTT) angle at ball release. The pitchers with inadequate forward trunk tilt at ball release demonstrated a lower forward upper torso flexion angle compared to the pitchers with normal forward tilt at ball release. There were no differences in the forward upper torso flexion angle between pitchers with high vs. normal, or excessive vs. normal forward trunk tilt at ball release.

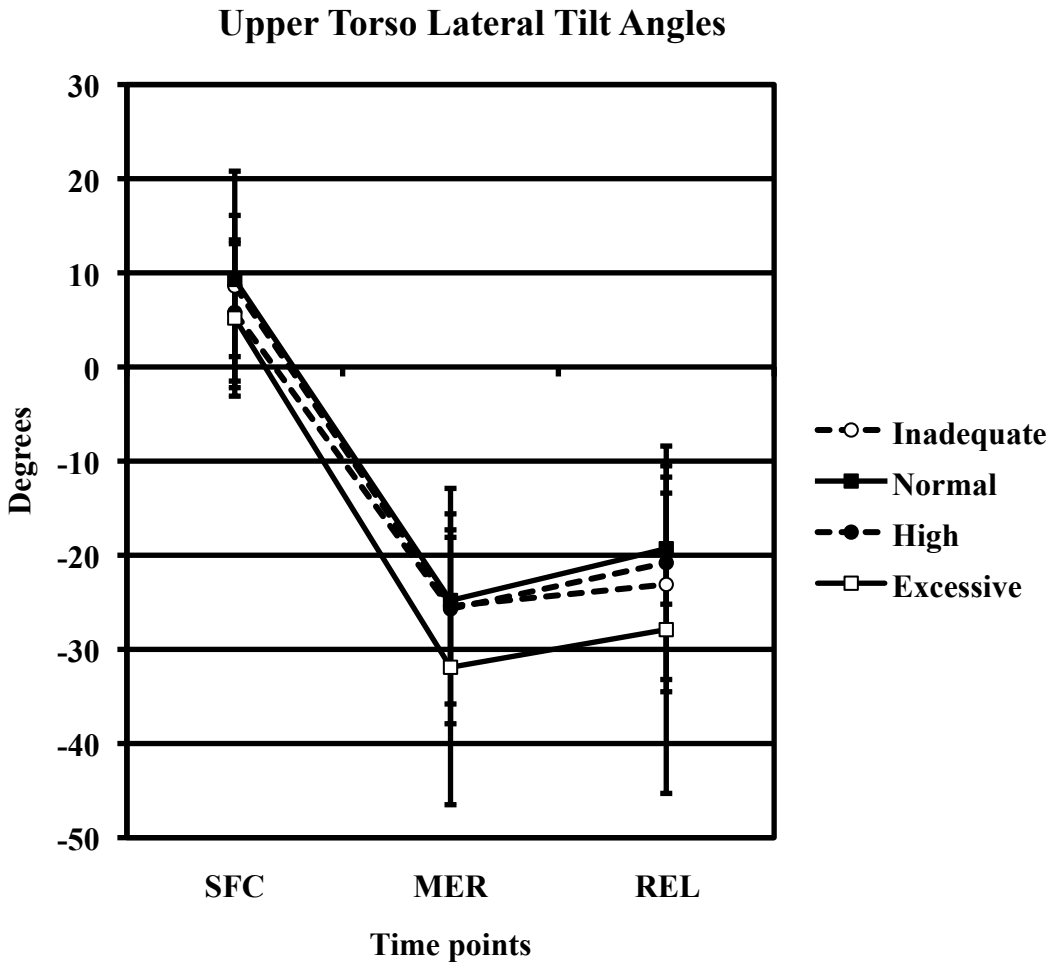



**Figure 28.** Upper torso lateral tilt angles in pitchers with inadequate, normal, high, and excessive forward trunk tilt angle (FTT) at ball release. There were no significant between-group differences in the upper torso lateral trunk tilt angles.

# CHAPTER 5

# DISCUSSION

## 5.1 Introduction

Pitching using a technique that places undue stress on the shoulder and elbow joints, have been identified as one of the risk factors for the pitching-related upper extremity injuries.[11, 18] Therefore, identifying the kinematic parameters that are associated with increased joint loading would lead to prevention of upper extremity injuries. There are a number of laboratory studies that identified the three-dimensional kinematic parameters that are associated with an increased joint loading.[7, 8, 176-178, 199, 201, 203] Unfortunately, the kinematic parameters identified in these studies cannot be detected without laboratory-based motion capture systems.[147] Therefore, in order for the coaches, parents, and sports medicine clinicians to identify pitchers with a technique that predisposes them to injuries, we must focus on the movement patterns that can be identified using video cameras (observable technical errors), and investigate their effects on joint loading.[44]

In this study, we focused on the observable technical errors of the trunk because the trunk is the proximal base of the upper extremity segment, and therefore the kinematics of the trunk segment have a direct influence on the upper extremity kinematics and kinetics.[7, 8, 89, 158, 165, 166] The purpose of the study was to examine the effects of the technical errors of the trunk on joint loading, performance, and quality of pitching technique. The specific technical errors that were examined in this study were 1) open shoulder (OS), 2) backward lean at

stride foot contact (BLSFC), 3) lateral lean at stride foot contact (LLSFC), 4) lateral lean at maximal shoulder external rotation (LLMER), and 5) inadequate forward trunk tilt at ball release (FT). These technical errors were identified through a review of literature and books written by the experienced pitching coaches.[44, 76, 94, 95]

The effects of the technical errors on ball speed and joint loading (**Specific aim 1 a & d**) will be discussed first. This will be followed by discussions on the cumulative effects of the technical errors on ball speed and joint loading (**Specific aim 2 a & d**), effects of the technical errors on pitch accuracy (**Specific aims 1&2 b**), effects of the technical errors on quality of pitching technique (**Specific aims 1&2 c**), and clinical implications of the study observations.

### 5.2 Effects of the Lateral Lean at Maximal Shoulder External Rotation (LLMER) on Ball Speed and Joint Loading

In this study, pitchers were determined to have LLMER, if their head was laterally deviated from the vertical line crossing the stride foot ankle by more than a head width at the instant of maximal shoulder external rotation (**Figure 2**). We observed that the pitchers who demonstrated LLMER produced a higher ball speed but also experienced a greater shoulder and elbow joint loading. Specifically, the pitchers with LLMER experienced a greater peak elbow varus moment, peak shoulder internal rotation moment, and greater peak proximal forces at the shoulder and elbow joints compared to the pitchers who did not demonstrate the error. This observation is in line with what was reported in the previous studies.[7, 132] Matsuo et al[132] used a computer simulation to predict the peak elbow varus moment when the trunk lateral tilt and the shoulder abduction angles at ball release were systematically altered. The analysis indicated that a greater lateral trunk tilt would result in a greater peak elbow varus

moment, when the shoulder is abducted to 90-100°.[132] Similarly, Aguinaldo et al[8] reported a trend that the greater maximal lateral trunk tilt angle was correlated with an increased elbow varus moment.

The elbow varus moment peaks immediately before the instant of maximal shoulder external rotation, and resists the external valgus moment that increases the stress within the medial elbow structures (ulnar collateral ligament (UCL), ulnar nerve, and flexor pronator mass), and increases sheer and compressive stress on the lateral and posteromedial osseous structures.[9, 139-141] Additionally, the proximal force at the elbow, which peaks immediately prior to ball release, resists the external force that acts to distract the articulating surfaces, and thus increases the tensile stress on the joint capsule, anterior portion of the UCL, biceps brachii and the flexor-pronator mass.[183] The greater stress developing within these anatomical structures have been linked to common pitching-related upper extremity injuries, such as UCL sprain, medial epicondylitis, osteocondritis, and ulnar neuropathy.[9, 139-141]

At the shoulder, the internal rotation moment, which peaks before the instant of maximal shoulder external rotation, resists the external external rotation moment, and thereby increases the stress on the biceps-labral complex, coracohumeral ligament, rotator cuffs, and glenohumeral joint capsule.[105, 109, 110, 112, 118, 119, 174, 196] Similarly, the proximal force at the shoulder that peaks just prior to ball release resists the external force that distracts the glenohumeral joint, and thus increases the tensile stress on the glenohumeral joint capsule, long head of the biceps brachii, and the rotator cuffs.[98, 99] The greater stress placed on these structures has been linked to a superior labrum anterior to posterior (SLAP) lesion, rotator cuff tendinosis, and glenohumeral joint instability.[111, 164, 185, 215]

Huang et al[96] compared the pitching kinematics between the pitchers with and without a recent history of pitching injuries, and reported that the pitchers with an injury history demonstrated a greater lateral trunk tilt at ball release. This finding supports the idea that LLMER is associated with an increased joint loading, and thus increased risk of injuries. In our study, there were 13 pitchers who reported a history of pitching-related upper extremity injuries in the past 2 years. While not statistically significant, there was a trend that the prevalence of LLMER was approximately 1.7 times higher among the pitchers with an injury history compared to the pitchers without an injury history. This trend may support the findings from a study by Huang et al,[96] and the idea that LLMER may be related to an increased injury risk. However, an analysis using a larger number of pitchers is needed to further investigate the association between LLMER and injury, since this analysis was under-powered (post-hoc power = 0.61). This analysis is also limited by that fact that pitchers with variety of injuries were included in the analysis. Also, a retrospective nature of the analysis precludes us from determining whether the pitchers with an injury history demonstrated the error prior to the time of injury, or if the error developed after the injury.

In our data, there were moderate correlations between ball speed and shoulder internal rotation moment (r = 0.460), elbow varus moment (r = 0.411), and proximal forces at the shoulder (r = 0.620) and elbow (r = 0.608) joints. Therefore, ball speed could have been included in the comparisons as a covariate. We did not do so due to a fear of over-correcting for the effects of ball speed, since ball speed is associated with pitcher's height (r = 0.511) and mass (r = 0.294), and the kinetic values were normalized to these variables. Furthermore, ball speed is an outcome of the pitching kinematics and kinetics, and not a factor that contributes to ball speed. Perhaps, ball speed should be included in the model as a covariate,

if the ball speed reflected the pitcher's effort level (i.e. how hard they pitched). However, pitching is a task that is performed with a maximal effort within the task constraint (i.e. need to hit the target), and we have no reason to suspect that the pitchers with LLMER provided a greater effort compared to the pitchers without LLMER.

We did, however, conduct follow up analyses to compare joint loading between the pitchers with and without LLMER, after controlling for the effects of speed (ANCOVA). We observed that when ball speed was included in the comparisons as a covariate, the group differences in shoulder internal rotation moment ($p=0.094$), elbow varus moment ($p = 0.111$), and proximal force at the shoulder ($p = 0.075$) became statistically insignificant. The difference in elbow proximal force ($p = 0.023$) remained statistically significant (**Table 40**). Upon examination of the relationships between ball speed and joint loading variables, we observed that the regression lines (least-squares) of the two groups (LLMER and no LLMER) were near parallel for the proximal forces at shoulder and elbow joints (**Figure 29 & 30**). The regression lines appeared less parallel for elbow varus moment (**Figure 31**) and shoulder internal rotation moment (**Figure 32**).

These observations suggest that pitchers with LLMER may have experienced increased joint loading because LLMER is associated with production of higher ball speed, which is related to increased joint loading. However, observation of the adjusted means of the kinetic variables between the pitchers with and without LLMER showed that the pitchers with LLMER tended to experience higher joint loading, even after controlling for the effects of ball speed. Additionally, dissimilarity in the regression lines for the elbow varus and shoulder internal rotation moments between pitchers with and without LLMER indicates. that

further investigation using a larger number of pitchers is needed to determine whether or not LLMER is associated with increased joint loading independent of ball speed.

**TABLE 40**: Comparisons of the shoulder and elbow peak kinetic variables between the pitchers with and without lateral lean at maximal external rotation (LLMER) **adjusting for the effects of ball speed**

**TABLE 40**

| | Technical errors | | p | Effect size† | Power |
|---|---|---|---|---|---|
| | Yes (n=31) | No (n=41) | | | |
| Peak elbow proximal force (%BW) | 101.4±2.0 (CI: 97.3-105.5) | 95.0±1.8 (CI: 91.5-98.6) | 0.023 | 0.45 | 0.457 |
| Peak elbow varus moment (%BW*Height) | 4.20±0.13 (CI: 3.93-4.46) | 3.91±0.11 (CI: 3.68-4.14) | 0.111 | 0.36 | 0.326 |
| Peak shoulder proximal force (%BW) | 101.9±2.24 (CI: 97.5-106.4) | 96.5±1.94 (CI: 92.6-100.3) | 0.075 | 0.34 | 0.297 |
| Peak shoulder internal rotation moment (%BW*Height) | 4.11±0.13 (CI: 3.85-4.36) | 3.81±0.11 (CI: 3.6-4.04) | 0.094 | 0.39 | 0.358 |

BW = Body weight, CI = 95% Confidence interval
† Cohen's d effect size

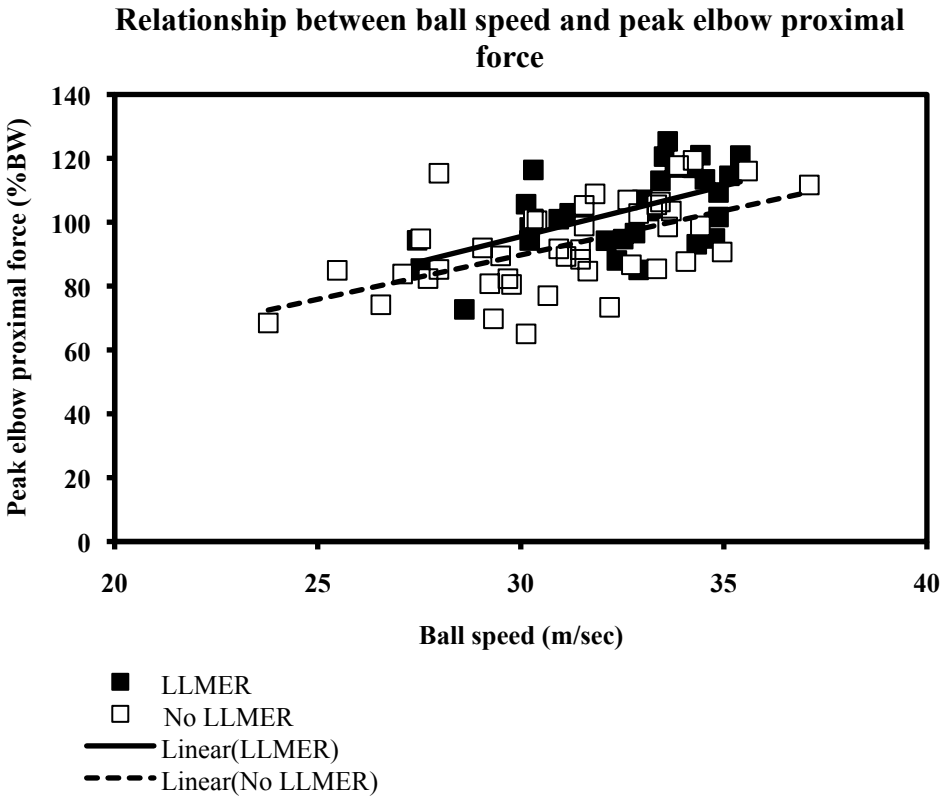



**Figure 29**: Relationship between ball speed and peak elbow proximal force

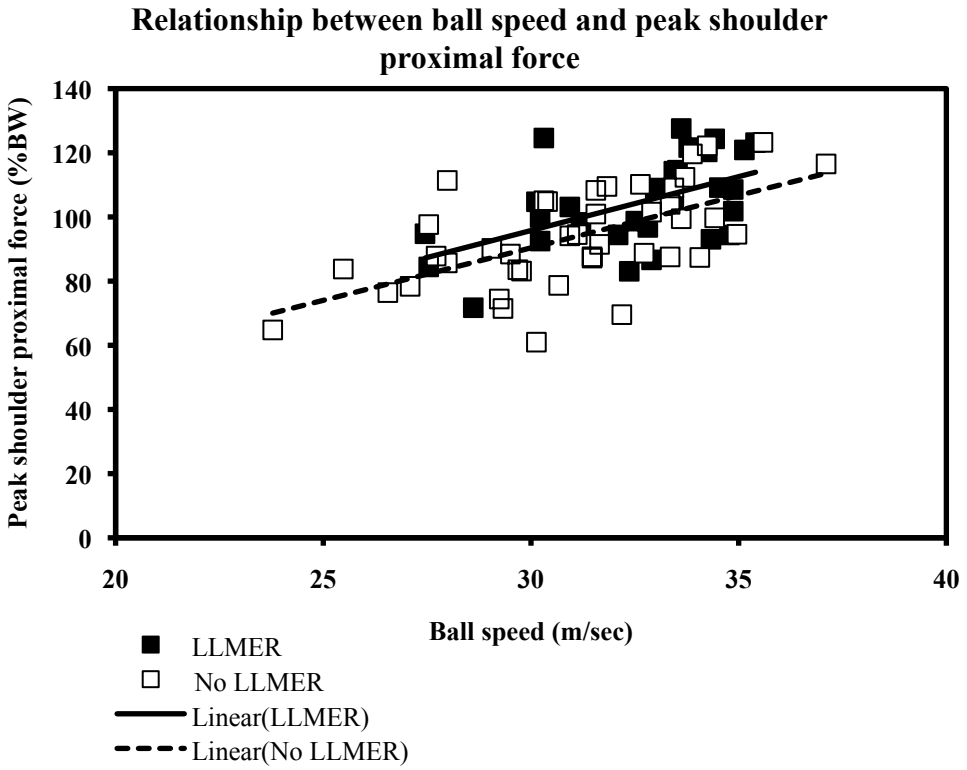



**Figure 30**: Relationship between ball speed and peak shoulder proximal force

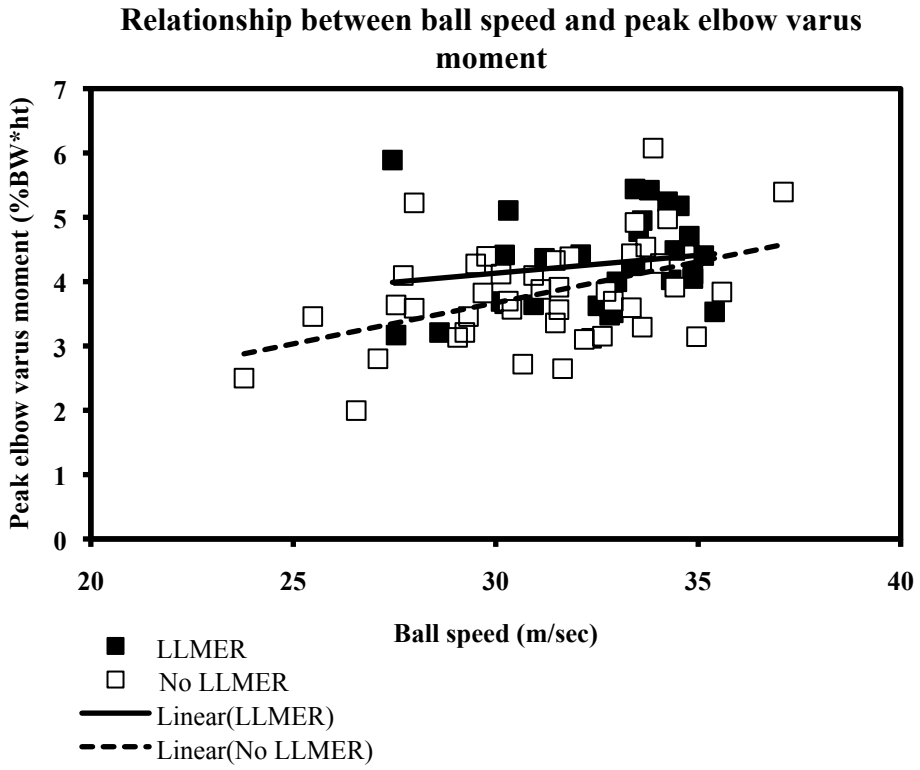



**Figure 31**: Relationship between ball speed and peak elbow varus moment

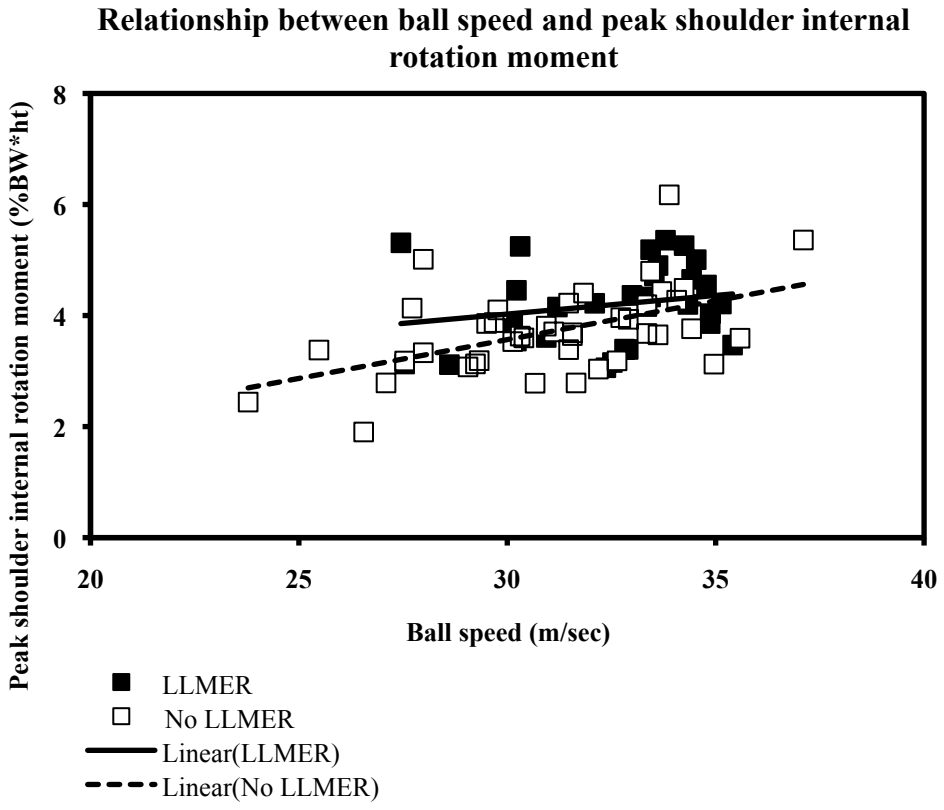



**Figure 32**: Relationship between ball speed and peak shoulder internal rotation moment

In effort to better understand how the pitching kinematics differed between the pitchers with and without LLMER, the upper extremity and trunk kinematics were compared between the pitchers with and without LLMER. Surprisingly, we observed no differences in the shoulder or elbow joint angles, angular velocities, or temporal variables between the groups. The only kinematic differences observed were the upper torso orientations at stride foot contact, maximal shoulder external rotation, and ball release. Specifically, the pitchers with LLMER demonstrated more extended upper torso at the stride foot contact and less rotated and more laterally flexed upper torso at maximal shoulder external rotation and ball

release (**Figure 22-24**). Based on these observations, it appears as though the pitchers with LLMER used more frontal plane trunk movement and less transverse plane movement during the arm-cocking and acceleration phases of pitching. During arm-cocking and acceleration phases of pitching, trunk movement in the frontal plane (lateral flexion towards the contralateral side) is assisted by the gravitational force. On the other hand, trunk movement in the transverse plane is not assisted by gravity, and thus needs to be produced using hip and trunk musculature. Although speculative, it is possible that LLMER is a compensatory pattern adopted by the pitchers who cannot produce strong trunk rotation due to previous injuries or weakness in hip and abdominal musculatures.

The effect of the upper torso kinematics on the forces and moments at the upper extremity joints may be explained by their influence on the linear acceleration of the throwing shoulder. During pitching, the linear acceleration of the shoulder is mainly produced by the rotation of the upper torso in the transverse plane and the circular movement of the throwing shoulder about the non-throwing shoulder. The linear acceleration of the shoulder that is caused by the upper torso rotation produces a horizontal abduction moment about the arm center of mass (COM) and valgus moment about the forearm COM. Because of the anatomical configuration of the elbow joint that limits the frontal plane movement (valgus/varus), the valgus moment, in turn, creates the shoulder external rotation moment.

The pitchers with LLMER demonstrated a greater upper torso lateral flexion at the maximal shoulder external rotation. It is possible that the having a greater frontal plane upper torso movement resulted in additional linear acceleration of the throwing shoulder in a superior direction. When the shoulder is abducted and externally rotated during the late arm-cocking phase, the acceleration of the throwing shoulder in a superior direction would create

a shoulder adduction moment and an elbow valgus moment, and thus the shoulder external rotation moment.

The linear acceleration of the shoulder also affects the proximal forces at the shoulder and elbow joints by contributing to the linear acceleration of the arm, forearm, and hand/ball segments. The effects of the linear acceleration on the forces and moments at the upper extremity joints may explain why the pitchers with LLMER experienced a greater joint loading. However, further analyses that explain the cause and effect of the motion, such as an analysis of the motion-dependent accelerations and forward dynamics, is needed to confirm this hypothesis.

On average, ball speed in the pitchers with LLMER was 1.5 m/sec (3.3 miles per hour) faster than the ball speed in the pitchers who did not demonstrate the error. The increased ball speed would give the pitchers a competitive edge. At the same time, the pitchers with LLMER experienced approximately 10% greater elbow varus moment, shoulder internal rotation moment, and proximal forces at the shoulder and elbow joints, which may predispose them to the pitching-related upper extremity injuries. The conflicting effects of LLMER on the performance and joint loading creates a dilemma as to whether or not pitchers should be instructed to adopt this strategy.

Considering the prolonged time loss from sports and a potential need for surgery once injury had been sustained, we think that pitchers should avoid pitching with LLMER. Among all baseball players, pitchers are a subset of players with an increased risk of injuries.[39, 49, 108, 133] It is estimated that approximately 73-79% of all baseball injuries are associated with pitching.[39, 49, 133] At a high school level, approximately 10% of the injuries sustained during baseball are treated surgically, and 73% of the injuries that resulted in surgery are sustained

by pitchers.[108] A typical recovery time from elbow arthroscopic debridement, subacromial decompression, and ulnar nerve transposition ranges from 2 to 3 months, while a recovery from the repair of the torn superior labrum (SLAP repair) typically takes about 6 month, and a complete recovery from the UCL reconstruction takes about 12 to 18 months.[79, 161, 194, 208] Even for the injuries that do not require a surgery, 4-6 weeks of conservative treatment is recommended.[208]

Such a long time lost from baseball participation would cause a set back in the performance and skill development. Therefore, we consider that the potentially increased risk of injuries associated with LLMER outweighs the benefit of achieving a higher ball speed, particularly when the mean gain in ball speed is 3.3 miles per hour. Moreover, there are other strategies, besides LLMER, that pitchers can use to achieve a higher ball speed. A greater peak ground reaction force during a push-off,[128] greater knee flexion at stride foot contact,[204] and greater knee extension angle at ball release[131, 204] have been linked to higher ball speed. These technical parameters should be addressed before resorting to LLMER to achieve a higher ball speed.

As we reviewed the videos from the pitching trials, we noticed that many of the pitchers with LLMER appeared to have an excessively closed stance offset (**Figure 33**). In fact, our analysis demonstrated that the pitchers with an excessively closed stance offset were almost 3 times more likely to demonstrate LLMER than the pitchers who took a stride towards the target. This observation suggests that the excessively closed stance offset may be one of the factors that guide the pitchers to demonstrate LLMER. If the pitcher with LLMER also demonstrated an excessively closed stride offset, correction of the excessive stride offset by instructing the pitcher to take a stride towards the target, may help correct LLMER.

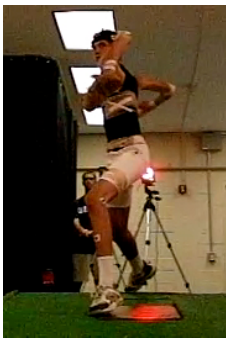


**Figure 33**: A pitcher demonstrating an excessive closed stride offset

### 5.3 Effects of Backward Lean at Stride Foot Contact (BLSFC) on Ball Speed and Joint Loading

Backward lean is one of the common technical errors at the stride foot contact. Pitchers were determined to have this technical error if their head was deviated from the vertical line crossing the stride foot ankle (**Figure 3**). Contrarily to our hypothesis, we observed that BLSFC was not directly associated with a ball speed or joint loading. This may be attributed to the fact that joint loading does not peak until the instant of maximal shoulder external rotation and ball release.

However, the importance of this technical error is that all pitchers who demonstrated BLSFC (13 out of 13) proceeded to demonstrate LLMER, which was associated with an increased joint loading. Supplementary to this observation, we observed that the sagittal plane trunk orientation (flexion/extension) at the stride foot contact was correlated with the frontal plane trunk orientation (lateral flexion) at the maximal shoulder external rotation. After the stride foot contact, pitcher's upper torso that was parallel to the direction of throw starts to rotate 90° to become perpendicular to the direction of throw. The correlation between the trunk orientations at stride foot contact and maximal shoulder external rotation

illustrates how the sagittal plane trunk orientation becomes translated into a frontal plane movement as the upper torso takes a 90° turn during the arm cocking phase (**Figure 34**).

This observation illustrates the importance of having a proper upper body alignment at the stride foot contact, in order for the pitchers to avoid LLMER. Furthermore, the observation suggests that when the pitchers demonstrate both LLMER and BLSFC, addressing BLSFC may lead to a correction of LLMER. Therefore, while BLSFC is not directly associated with an increased joint loading, identification of this technical error may be meaningful as it offers a potential strategy to correct LLMER.

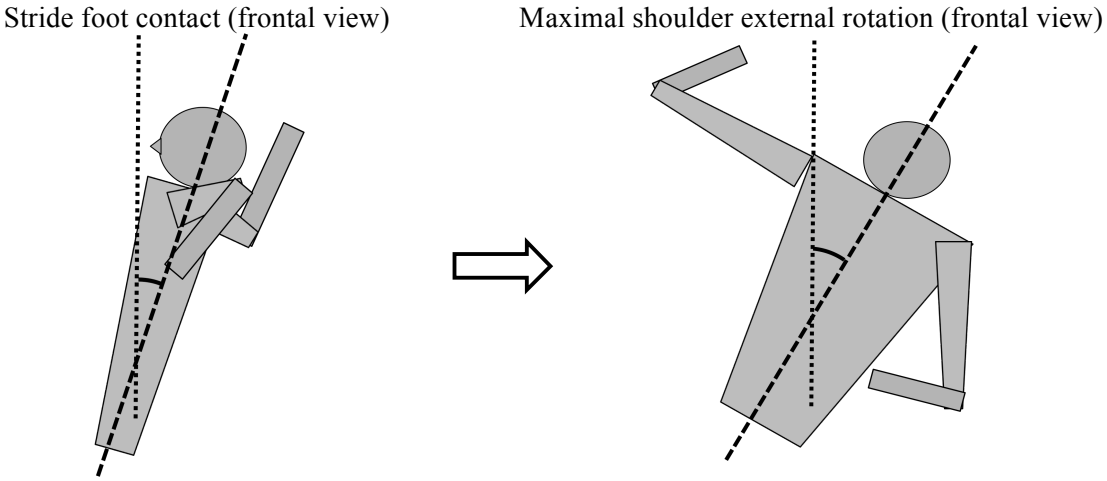



**Figure 34:** Translation of the sagittal plane trunk movement at stride foot contact to the frontal plane trunk movement at maximal shoulder external rotation

### 5.4 Effects of Inadequate Forward Trunk Tilt (FT) on Ball Speed and Joint Loading

Pitchers were considered to have inadequate FT, if the line passing through the middle of their trunk was tilted less than 20° from vertical at ball release. This threshold (20°) for the technical error was based on the previous literature, which stated that the

forward trunk tilt angle at ball release should be approximately 30°.[76] The pitchers with inadequate FT demonstrated a lower ball speed and lower proximal forces at the shoulder and elbow joints. However, there were only 5 pitchers who demonstrated inadequate FT in our sample, which limits the generalizability of the observation.

For this reason, we followed up this observation by examining how a ball speed and joint loading in pitchers with inadequate (<25°), high (35-45°), and excessive (>45°) forward trunk tilt (FTT) angles compare to that of the pitchers with normal (25-35°) FTT angle. Based on this classification, 11, 16, 23, and 22 pitchers demonstrated inadequate, normal, high, and excessive FTT angles, respectively. We observed that the pitchers with inadequate FTT angle demonstrated a lower ball speed, lower peak shoulder proximal forces, and trends of lower peak elbow proximal forces and increased elbow extension moment, compared to the pitchers with normal FTT. The observation that the pitchers with inadequate FTT produced a lower ball speed is in agreement with the hypothesis and the reports from the previous studies.[187, 204 131] Mastuo et al[131] reported that the trunk flexion angle was greater in collegiate and professional pitchers who produced high ball velocity (>38m/sec) compared to the pitchers who produced low ball velocity (< 34.2m/sec). Additionally, greater trunk flexion angle at ball release has been identified as one of the predictors of ball speed in previous studies.[187, 204]

We had originally hypothesized that the pitchers with FT (technical error) would demonstrate a greater joint loading. This hypothesis was based on the concept that an ineffective use of the forward trunk tilt would require the pitcher to compensate with their upper extremity to generate the momentum needed to produce a ball speed. However, in light of the effects of upper torso movement on the linear acceleration of the throwing shoulder

that was discussed earlier, it seems logical that the pitchers with inadequate FTT at ball release experienced lower peak proximal forces. An ineffective utilization of trunk movement during the acceleration phase would limit the production of linear acceleration of the upper body segments, and thus decrease the proximal forces at the shoulder and elbow joints.[166] While this error was associated with decreased joint loading, it is still considered a technical error, since it was also associated with on average 6.3 miles per hour lower ball speed.

It is worth noting that the pitchers with inadequate FTT angle (<25°) tended to experience a greater elbow extension moment compared to the pitchers with normal, high, and excessive FTT angle. This observation may be reflective of the pitcher's effort to compensate for the limited momentum generated by the trunk movement as originally hypothesized. The trend of a greater elbow extension moment in the pitchers with insufficient FTT may suggest that these pitchers may be placing a greater demand on the muscles around the elbow and stress on the osseous structures, especially if the elbow extension moment is not absorbed after ball release. The increased stress may predispose the pitchers to elbow injuries such as medial and lateral epicondylitis and olecranon stress fracture.[183] Further analysis is needed to better understand possible compensatory patterns at the upper extremity that are demonstrated by pitchers with ineffective trunk movement.

There were no statistically significant differences in ball speed or joint loading in the pitchers with high and excessive FTT relative to the pitchers with normal FTT. However, there was a general trend that the peak elbow varus moment, shoulder internal rotation moment, and the proximal forces at the shoulder and elbow joints were about 7% greater in the pitchers with an excessive FTT relative to the pitchers with normal FTT. Also, we

observed that, compared to the pitchers with normal FTT, the pitchers with an excessive FTT achieved a greater maximal shoulder external rotation angle, which has been identified as one of the predictors of the peak shoulder joint proximal force and elbow varus moment. Therefore, despite a lack of statistical significance, the pitchers with excessive FTT angles may be at a higher risk of injuries associated with increase joint loading. While the pitchers with excessive FTT tended to experience a greater joint loading, the ball speed was similar among the pitchers with normal, high, and excessive FTT. This supports the claim that 25-35° may be the optimal FTT angle at ball release for achieving high ball speed while sparing unnecessary joint loading.

While the upper torso flexion angle is difficult to visualize due to out of plane trunk movements (lateral flexion and rotation), the FTT angle represents the angle of the long axis of the upper torso viewed from the side (sagittal view). In this analysis, we used the FTT angle to classify the pitchers so that the observations from this analysis can be utilized by the coaches, parents, and sports medicine clinicians. It needs to be noted that the FTT angle does not correspond with the anatomical upper torso flexion angle, especially when there are out of plane trunk movements. In this study, the upper torso flexion angle at ball release was significantly lower for the pitchers with inadequate FTT compared to the pitchers with normal FTT (**Figure 27**). However, there were no differences in the upper torso flexion angles among the pitchers with normal, high, and excessive FTT. Instead, the pitchers with high and excessive FTT demonstrated less upper torso rotation at ball release compared to the pitchers with normal FTT (**Figure 26**), and the pitchers with excessive FTT tended to demonstrate a greater lateral flexion angle at ball release compared to the pitchers with inadequate, normal, and high FTT (**Figure 28**). This observation may be helpful when

developing instructions to increase or decrease the FTT angle in pitchers with high and excessive FTT.

It was also interesting to see that the pitchers with inadequate FTT at ball release not only demonstrated a lower flexion angle at ball release, but also at the instant of maximal shoulder external rotation. This suggests that the pitchers with FTT may need to achieve a greater upper torso flexion during the arm-cocking phase (before maximal shoulder external rotation), in order to achieve a greater FTT at ball release.

### 5.5 Effects of Open Shoulder (OS) on Ball Speed and Joint Loading

Open shoulder is a technical error characterized by an initiation of the upper torso rotation prior to the stride foot contact. The pitchers were determined to have OS, if the anterior aspect of the pitcher's front (non-throwing) shoulder was visible in the frontal view at the stride foot contact. We observed that there were no differences in ball speed or joint loading in pitchers with and without OS.

This observation did not support our hypothesis that the pitchers with OS would demonstrate lower ball speed, which was based on the observation in a previous study where the professional pitchers who presumably pitched faster (ball speed was not reported) than the high school and collegiate pitchers kept their upper torso closed longer compared to the collegiate and high school pitchers.[7] Additionally, we expected that the premature rotation of the upper torso would limit the use of the stretch shortening cycle and re-coil of the parallel elastic component of the trunk musculature when rotating the upper torso, and thus production of low muscle force.[87] While our hypothesis was rejected, a study by Aguinaldo

et al also reported no differences in the ball speed between the pitchers who initiated the upper torso rotation before vs. after the stride foot contact.[8]

There are a few factors that may explain the failure to demonstrate differences in ball speed and joint loading between the pitchers with and without OS. First, a lack of significant difference may be due to a small number of pitchers who demonstrated OS. In our sample of pitchers, there were only 4 pitchers (5.6%) who demonstrated OS. This low prevalence of the error was unexpected, since OS was present in 15% of the high school pitchers who participated in our pilot study, and 63% of the adolescent pitchers in the study by Davis et al.[44] The low prevalence of this technical error in our sample may be due to a sampling bias. Perhaps, the pitchers who expressed interest in participating in this study were the pitchers who have been exposed to more pitching technique instructions. Since "open shoulder" is an error that many parents and coaches are familiar with, this error may had been corrected as the pitchers learned how to pitch.

Second, the inter-rater agreement of this error (Kappa = 0.41, Maximum Kappa = 0.88) was lower compared to the other errors (Kappa: 0.88-0.94). We speculated that the low inter-rater agreement for this error may be due to the definition of the error used in this study ("the anterior aspect of the pitcher's front shoulder is visible at the stride foot contact"). This definition, which was adopted from the study by Davis et al,[44] may not accurately identify the pitchers with premature upper torso rotation, because a view of the anterior aspect of the front shoulder often gets blocked by the pitcher's front (non-throwing) arm, making it difficult for the raters to determine if the anterior aspect of the shoulder was facing the target.

The third factor that may explain why there were no differences in ball speed or joint loading between the pitchers with and without OS, is the definition of the instant of stride

foot contact. In this study, we adopted a definition used in the study by Davis et al,[44] which defined stride foot contact as the first frame in the video, in which any part of the foot became in contact with the ground. Some pitchers landed with their feet flat, while the others made the stride foot contact with their heels or toes first, and then gradually brought the entire foot in contact with the ground. Therefore, we felt as though the ratings of OS were affected by the pitcher's landing style. There were several pitchers whose shoulders were closed when their toes or heels first touched the ground, but were open when the entire foot came in contact with the ground (**Figure 35**). If these pitchers had landed with their feet flat, they would have been rated to have OS. Alternatively, the stride foot contact was considered an instant when the entire foot came in contact with the ground in the pitching evaluation form developed by the American Sports Medicine Institute.[147] This definition may provide the ratings of OS that is not affected by the different landing styles.

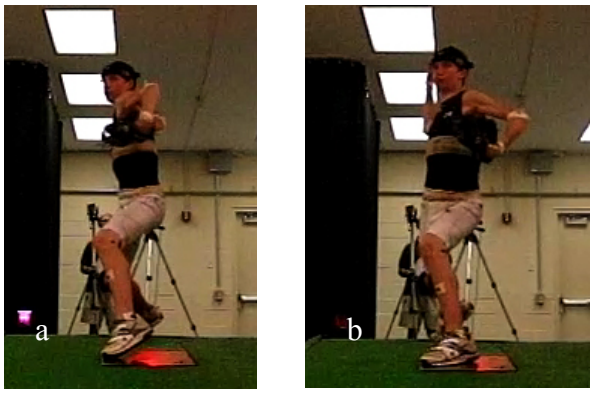



**Figure 35**. Illustration of a pitcher having closed shoulder at toe contact (a) and having open shoulder when the entire foot came in contact with the ground (b).

The observations from this study suggests that OS is not associated with low ball speed or increased joint loading. However, this observation needs to be interpreted with

caution, due to the factors discussed above. Evaluation of the effects of OS using better definitions for the error and the instant of stride foot contact is needed in order to better understand the effects of this technical error on ball speed and joint loading.

### 5.6 Effects of Lateral Lean at Stride Foot Contact (LLSFC) on Ball Speed and Joint Loading

The pitchers were determined to have LLSFC, if their head was positioned behind the vertical line crossing the stride foot ankle. Against our hypothesis, we observed that this technical error was not associated with decreased ball speed or increased joint loading. This technical error at stride foot contact was also not associated with LLMER, which was linked to increased joint loading. This technical error was examined in this study based on the pitching instruction used by the baseball coaches to "keep the head over the umbilicus" and "balanced between the feet" at stride foot contact.[94, 95] In one study, Werner et al[201] examined the effects of the timing when the head moved ahead of the hips on the peak shoulder distraction force. They reported that keeping the head behind the hips longer was associated with a lower shoulder proximal force, which suggests that LLSFC may be associated with decreased joint loading. However, the authors offered no explanations for this observation, and the observation has not been replicated in other studies.

The lack of significant differences in ball speed or joint loading may be attributed to the low number of pitchers who demonstrated this error (n=13) and/or the definition of the stride foot contact discussed previously. However, this observation may also exemplify that not all pitching instructions used by baseball coaches are supported by science. A leading pitching expert Tom House stated in his book that the conventional wisdom on pitching

technique is "an opinion that has been repeated so often by so may people for so long that it has subsequently become accepted as fact."[94, 95] The observation that LLSFC was not associated with performance or joint loading suggest that coaches and parents may not need focus on keeping the head over the umbilicus and balanced between the feet (frontal plane) at stride foot contact.

### 5.7 Cumulative Effects of the Technical Errors on Ball Speed and Joint Loading

In addition to the effects of the individual technical errors on ball speed and joint loading, cumulative effects of the technical errors were examined. We hypothesized that the pitchers with a greater number of technical errors would demonstrate a lower ball speed and greater joint loading. However, our results indicated that the total number of the technical errors demonstrated by the pitchers had no effects on ball speed or joint loading. This may be explained by the observation that only 2 of the 5 technical errors (LLMER and FT) were associated with ball speed and joint loading, and that one of which (FT) was demonstrated by only 5 (6.9%) pitchers. Moreover, LLMER and FT had the opposite effects on ball speed and joint loading. Specifically, LLMER was associated with an increased ball speed and joint loading, whereas FT was associated with a decreased ball speed and joint loading (except for the peak elbow extension moment). When not all errors influence the variables in the same direction the analysis can be obscured by a number of possible error combinations that participants may have. Therefore, evaluation of the cumulative effects of the technical errors may only be valid when all of the technical errors has been demonstrated to have effects on the variable of interest in the same direction.

### 5.8 Effects of the Technical Errors on Ball Accuracy

To date, no study has investigated the effects of pitching technique on an accuracy of the aim. In this study, we observed that the pitchers with high FTT demonstrated better accuracy compared to the pitchers with normal FTT. However, the accuracy of the aim was not different among the pitchers with and without the individuals errors, or among the pitchers with 0, 1, and 2 technical errors. While this observation may suggests that aim may be affected by some technical parameters, validity of our accuracy measurements may have been compromised by a few factors.

All data collection took place in an indoor research laboratory, which was approximately 100 feet long and 25 feet wide, with a ceiling height of 25 feet. While the pitchers were given an ample time to warm up and get accustomed to pitching inside the laboratory, some pitchers expressed that pitching in the narrow laboratory space made the backstop appear further away than the regulation distance. Another factor that may have affected the validity of our accuracy measurement is that the pitchers were asked pitch into a backstop, instead of a catcher's mitt. Many pitchers expressed awkwardness and difficulty aiming at the backstop as opposed to a mitt. Some pitchers and parents also expressed that the strike-zone indicated on the backstop was higher than the actual strike zone.

In a previous study that examined the effects of balance performance on ball accuracy, the pitching trials were conducted in the indoor practice facility, and the pitches were received by a catcher.[130] Perhaps, pitching in an open space and utilizing a catcher may have improved the validity of the accuracy measures in our study. However, the testing location was limited to the laboratory space from an equipment standpoint, and catchers were not available during data collections. For these reasons, despite our observations that some

pitching technique assessed in this study was associated with ball accuracy, the observations from this study needs to be interpreted with caution.

One consideration in assessing the effects of pitching technique on accuracy of the aim is that the accuracy may be more affected by the consistency of the movement, rather than the technique itself. During adolescence, pitching in games and practices result in skill refinement that is characterized by a decreased movement variability, improved consistency of the aim, and development of the movement coordination that is more economical and utilize multiple linked segment in a manner that produces optimal performance.[78, 129] Therefore, examination of the effects of movement variability on accuracy may be more appropriate than examining the effects of the technique itself. Furthermore, precision of the aim is just as important as the accuracy of the aim. Therefore, the effects of pitching technique and variability of the pitching technique on precision of the aim also need to be investigated.

### 5.9 Effects of the Technical Errors on Quality of Pitching Technique

Prior to the study, we were aware of the poor validity of the pitching evaluation form developed by the American Sports Medicine Institute (**Appendix 2**).[147] Most of the 24 items on the pitching evaluation form has been shown to have poor validity against the three-dimensional kinematic data collected using the motion capture system,[147] and the total score on the evaluation form has not been linked to increased joint loading or risks of injury.[126] However, we proceeded to use this form because we hoped to demonstrate that the technical errors examined in this study would be associated with the overall "poor" quality or

impression of the pitching technique, and this form was the only available tool that allowed systematic assessment of the pitching technique.

In reviewing the pitching evaluation form, we identified several items that addressed more than 1 aspect of the movement. For example, in order to earn a score on the item on a proper follow-through, pitchers needed to demonstrate: 1) horizontal trunk orientation when the throwing hand was farthest from the trunk, 2) hand located outside of the extended lead leg, and 3) back of the shoulder visible to the target. Since these three aspects of the movement can be performed correctly/incorrectly independently from one another, we divided this item into "back of the shoulder is visible during follow-through" and "hand finished outside the stride leg". The part on the trunk being horizontal was eliminated because the trunk did not come close to being horizontal even in the pitchers with the greatest amount of forward trunk tilt at ball release. The other modifications made to the original form are summarized in **appendix 3**. As a result, the original 24-item form was modified to a 30-item form in order to achieve a better inter-rater reliability of the items (**Appendix 1**).

Despite this effort, the between-rater agreement was poor for 7 of the 30 items on the pitching evaluation form. Even for the items with higher inter-rater agreement, unclear definition and cutoff points between the correct and incorrect technique, and difficulty viewing out of plane joint angles created challenges in rating the items. We observed that the quality of pitching technique was lower in the group of pitchers with FT, and in the pitchers with inadequate FTT angle (<25°) compared to the pitchers with normal FTT. However, we do not place confidence in this observation given the challenges we had in the rating of the individual items. In future, development of a valid evaluation form that allows screening of

the pitching technique that are associated with performance and increased joint loading would be useful for the coaches and parents working with baseball pitchers.

### 5.10 Clinical Implications

The observations from this study has implications for the prevention of pitching-related upper extremity injuries. We identified that LLMER is associated with increased joint loading. In addition, we observed a trend that inadequate or excessive FTT angle may be associated with increased joint loading. Using video recordings, these technical parameters can be identified by baseball coaches, parents, and sports medicine clinicians to identify the pitchers with potentially increased risk of injuries. In this study, high speed video cameras (300 fps) were used to identify the technical errors. Since a majority of the video cameras on the market use a standard capturing rate (60 fps), we re-rated the videos from the first 30 pitchers (1 pitch/pitcher) after down sampling the videos to 60 fps, and compared the error ratings based on the high speed vs. standard frame rate videos. We observed that there were high agreements between the errors rated using the high speed and standard-rate videos (OS: Kappa ($\kappa$) = 0.651, BLSFC: $\kappa$ = 1.00, LLSFC: $\kappa$ = 0.871. LLMER: $\kappa$ = 0.842, FT: $\kappa$ = 0.870). Therefore, coaches, parents, and sports medicine clinicians without high speed video cameras can still use standard video cameras to identify the technical errors.

The observations from this study also provide an insight as to how to modify the technical errors. We observed that all pitchers with BLSFC also demonstrated LLMER, and that the sagittal plane trunk orientation at the stride foot contact was correlated with the frontal plane trunk orientation at the maximal shoulder external rotation. These observations indicate that instructing the pitchers to keep their head positioned directly over the foot, and

keeping the upper torso slightly flexed at the stride foot contact may help decrease the upper torso lateral flexion at the maximal shoulder external rotation, and thereby avoid LLMER. Additionally, the pitchers who were rated to have an excessively closed stance offset, were almost 4 times likely to demonstrate LLMER. Therefore, if the pitchers with LLMER also demonstrated an excessively closed stride offset, instructing the pitchers to stride directly towards the hitter, may help correct LLMER. The pitchers with LLMER also tended to use more frontal plane and less transverse plane upper torso movement. Emphasizing the need to rotate the upper torso towards the target may help them utilize the transverse plane trunk motion.

The pitchers with inadequate FTT at ball release also demonstrated less FTT at the maximal shoulder external rotation. Therefore, when instructing the pitchers with inadequate FTT to increase the FTT angle, coaches and parents may need to focus on pushing the chest forward towards the target as they rotate the upper torso during the arm-cocking phase, instead of focusing on the ball release. As discussed above, there were no differences in the upper torso flexion angles among the pitchers with normal, high, and excessive forward trunk tilt. However, we observed that the pitchers with excessive FTT had less rotated upper torso rotation than the pitchers with normal FTT, and also tended to have a greater lateral trunk flexion angle at the maximal shoulder external rotation and ball release. Therefore, these pitchers may need to be instructed to rotate their upper torso towards the target to achieve a normal FTT angle.

Identification of the pitchers with LLMER and inadequate or excessive FFT angle, and providing them with instructions to modify the errors may help decrease the joint loading and thereby prevent the pitching-related upper extremity injuries. However, studies need to

be conducted in order to determine whether the correction of these technical errors would actually result in decreased joint loading.

### 5.11 Limitations

There are several limitations that need to be acknowledged. Firstly, pitching trials took place indoors in a research laboratory. While we made every effort to simulate the normal pitching environment (i.e. indoor pitching mound, regulation pitching distance), pitching in an unfamiliar setting may have influenced the pitching performance. Most pitchers expressed that the ball speed that was recorded during testing were a little lower (by about 2-3 miles per hour) than the ball speed they typically achieve. We speculate that this may be attributed to the pitching environment, and the fact that pitchers were not allowed to wear cleats, which gives them a grip for a strong push off and landing.

Secondly, when calculating joint kinetics, linear acceleration of the ball was assumed to be equal to the linear acceleration of the reflective marker on the 3$^{rd}$ metacarpal head. The point of application of the external force of the ball acting on the hand was also assumed to be at the center of mass of the hand segment. These assumptions were made because the reflective markers could not be placed on the ball during the pitching trials. These assumptions likely have resulted in underestimation of the joint kinetics, since center of the ball is located more distally than the marker on the 3$^{rd}$ metacarpal head, and the point of application of the external force is also located more distally than the hand center of mass. Use of instrumentation that allows better estimation of ball acceleration and the point of application of the external force on the hand would yield more accurate joint kinetics. However, we believe that the influence of these assumptions on joint kinetics were systematic, and therefore did not affect the comparisons.

Thirdly, the timing of ball release was assumed to occur on the 4th frame (0.013second) after the wrist surpassed the elbow in the direction of throw. Again, this assumption was made due to inability to place the reflective marker on the ball during pitching trials. However, we consider this was an acceptable estimation given that ball release occurred on the 4th frame in over 60% of the pitching trials from the first 15 pitchers (through observations of the high speed video), with ball release occurring between 3rd and 5th frame after the wrist surpassed the elbow in all 15 pitchers. A similar method has been used in a number of previous studies,[59, 60, 71, 74] and we observed that this estimation method had much better agreement with the observed timing of ball release than the other method used in previous studies (i.e. instant of peak velocity of the 3rd metacarpal head marker[201]).

Lastly, the videos that were used to identify the technical errors were captured at 300 fps, which is a higher rate that the most video cameras on the market (60 fps). Therefore, the technical errors identified in this study may not be as easily detectable with the standard video cameras. However, we observed that there were high agreements between the errors rated using videos showing the pitching technique at 300fps vs. 60fps videos.

## 5.12 Future Studies

This study was only the second study that investigated the effects of observable technical errors on performance and joint loading. As stated previously, in order for coaches, parents, and sports medicine clinicians to be able to identify pitchers with a technique that predisposes them to injuries, we must focus on the movement patterns that can be identified using video cameras, and investigate their effects on joint loading. In this study, we were focused on the trunk moment. Therefore, more studies are needed to investigate the

observable technical errors in the other aspects of the pitching skill. One of the goals of this line of this research is to develop a valid pitching technique screening tool that can be used to identify pitchers with an increased risk of injuries. In order to achieve this goal, we must identify more observable technical errors that are associated with increased joint loading, and conduct a prospective cohort study to determine whether the screening tool can predict an injury risk. Future studies should also investigate the effective ways to instruct or modify a pitching technique, and the effects of pitching technique modification on performance and joint loading. Such studies will lead to a development of long term injury prevention programs that can be implemented in community settings.

### 5.13 Conclusions

The observations from this study indicate that LLMER is a strategy that pitchers take in order to achieve higher ball speed at an expense of increased joint loading at the shoulder and elbow joints. Additionally, there was a trend that an inadequate (<25°) and excessive (>45°) FTT at ball release may be associated with the joint loading that are linked to injuries. These technical errors should be avoided considering the prolonged time loss that is expected once the pitchers become injured. These technical parameters can be observed using video cameras. Therefore, coaches, parents, and sports medicine clinicians can identify pitchers with these technical errors through screening of a pitching technique. The kinematic comparisons between the pitchers with and without the technical errors identified possible strategies that can be used to modify the technical errors. Using these strategies, coaches, parents, and sports medicine clinicians may be able to correct the technical errors and thereby prevent the pitching-related upper extremity injuries.

# APPENDIX 1: MODIFIED AMERICAN SPORTS MEDICINE INSTITUTE PITCHING EVALUATION FORM

**(I) Wind up**

1) Head position during a wind up (1)

__Yes __ No Pitcher's head remain balanced on the pivot foot.

2) Lower extremity movement at max knee-lift (2)

__Yes __ No Pitcher's lower body (hips) remains over the pivot foot (has not travelled toward home-plate) until the stride knee starts to descend.

3) Stance knee bending angle at max knee-lift (2)

__Yes __ No Pitcher's stance knee is slightly bent (<15 degrees).

If no:
__ Pitcher's stance knee is too straight
__ Pitcher's stance knee is too bent

**(II) Early Stride**

4) Timing of hand separation (3)

__Yes __ No Hand separation occurs as the stride hip moves towards the target.

If no:
__ Hand separation occurs early
__ Hand separation occurs late

5) Hand/finger position (3)

__Yes __ No Fingers remain on top of the ball.

6) Counter arm movement (9)

__Yes __ No Throwing hand moves down, back, and up into a cocked position.

7) Stride hip movement (4)

__Yes __ No Lateral aspect of the lead hip faces the plate until just before foot contact.

**(III) Stride foot contact**

8) Hand position (10)

__Yes __ No Throwing hand is directed to shortstop (RHP)

9) Forearm position (10)

__Yes __ No Wrist is positioned above the elbow

10) Shoulder abduction (11)

__Yes __ No Throwing arm is level with the shoulders

If no:
__ Throwing elbow is below the line of the shoulders.
__ Throwing elbow is significantly higher than the shoulder line.

11) Elbow flexion (12)

__Yes __ No Throwing elbow is flexed to approximately 90 degrees as the lead foot contacts the mound.

If no:
__ Throwing elbow is flexed toward the pitcher's head.
__ Throwing elbow is too straight.

12) Weight distribution (head position) at foot contact (6)

__Yes __ No Head forms an even triangle with the feet

If no:
__ Head has moved too far forward
__ Head is lagging behind

13) Stride knee flexion at foot contact (6)

__Yes __ No Angle behind the stride knee is 120-145 degrees when the stride foot makes full contact with the mound.

If no:
__ Stride knee is too straight
__ Stride knee is too flexed

14) Stride length (5)

__Yes __ No Stride length is 80-90% of the pitcher's height.

If no:
__ Stride length is substantially less than the pitcher's height
__ Stride length exceeds the pitcher's height

15) Stride offset (7)

__Yes __ No Stride foot is grounded within 10cm (4 inches) of an imaginary line from the instep of the pivot foot (medial malleolus) to home plate.

If no:
__ Stride is too closed
__ Stride is too open

16) Foot angle at contact (8)

__Yes __ No Toes of the stride foot (when in complete contact with the mound) are rotated slightly (~30degrees) inward.

If no:
__ Front foot angle is too closed
__ Front foot angle is too open

**(IV) ARM COCKING**

17) Maximum elbow flexion during arm cocking (16)

__Yes __ No Throwing elbow does not flex beyond 70-90 degrees as the upper torso rotates toward the hitter.

If no:
__ Throwing elbow collapses inward toward the pitcher's head.
__ Throwing elbow is too straight.

18) Maximum external rotation (17)

__Yes __ No Forearm become parallel or close to perpendicular with the trunk as the trunk faces the hitter.

19) Timing of maximum external rotation (17)

__Yes __ No Maximum external rotation is reached as the trunk faces the hitter.

If no:
__ Maximum external rotation is reached before the trunk faces the hitter.
__ Maximum external rotation is reached after the trunk faces the hitter.

20) Timing of hip/shoulder rotation (13)

__Yes __ No Pelvis rotation precedes the upper torso rotation.

21) Trunk arching (14)

__Yes __ No Trunk is hyper-extended and upper torso remains vertical as the shoulders rotate toward the hitter.

22) Use of glove arm (15)

__Yes __ No Glove is at the level of the non-throwing elbow and pulled close to the body as the pitcher's shoulders rotate toward the plate.

**(VI) BALL RELEASE**

23) Trunk-arm alignment (transverse plane) at ball release (21)

__Yes __ No Upper arm is approximately in line with the body-line at release

If no:
__ Arm is too far behind the line of the trunk
__ Arm is too far ahead of the trunk - the pitcher leads with the elbow.

24) Shoulder abduction (22)

__Yes __ No Elbow is at or slightly above the line of the shoulders

If no:
__ The elbow is too far below the shoulders
__ The elbow is too far above the shoulders

25) Elbow flexion (23)

__Yes __ No Elbow is flexed approximately 20 degrees as the ball leaves the pitcher's hand.

If no:
__ Elbow is too flexed
__ Elbow is straight or hyper-extended

26) Trunk flexion (20)

__Yes __ No Trunk is flexed forward approximately 60 degrees at release (30 degrees from vertical)

If no:
__ Trunk is too upright
__ Trunk is too flexed

27) Lateral trunk tilt (21)

__Yes __ No Trunk is tilted approximately 20 degrees toward the non-pitching side.

If no:
__ Trunk is too upright
__ Trunk is tilted too far

28) Knee flexion (18)

__Yes __ No Stride knee is straighter at ball release than at foot contact

**(VI) DECELERATION**

29) Trunk follow-through (24)

__Yes __ No Back of the shoulder is visible.

30) Arm follow-through (24)

__Yes __ No Hand finishes outside the leg.

## APPENDIX 2: AMERICAN SPORTS MEDICINE INSTITUTE PITCHING EVALUATION FORM

# PITCHING MECHANICAL EVALUATION FORM

*Based on biomechanical data collected at the American Sports Medicine Institute*
*Birmingham, Alabama 1999*

- Provides quality objective feedback
- Helps detect mechanical flaws which may lead to injury or decreased performance
- Simple to complete - requires only a camcorder!

**EVALUATION DETAILS:**

Pitcher's name:_____
Date of test: _____
Age: _____
Team/Park: _____
Average radar gun/speed: _____
Evaluator: _____

**HOW TO FILM YOUR PITCHER:**

**Anterior View:**
Right-handed pitcher
Three metres (10 feet) behind the right-handed batter's box.
Left -handed pitcher:
Three metres (10 feet) behind the left-handed batter's box.

---

**Lateral View:**
Right-handed pitcher
*On the home-third base line at a point 90 degrees to the pitching rubber.*
Left-handed pitcher:
*On the home-first base line at a point 90 degrees to the pitching rubber.*

---

**Posterior View:**
Right-handed pitcher
*Halfway between the centre of the pitching rubber and second base.*

Left-handed pitcher:
*Halfway between the centre of the pitching rubber and second base.*

Place the camera on a tripod. Zoom in to fill as much of the view as possible with the pitcher, allowing for stride length.
Use the highest possible shutter speed to minimise blur.
Record at least 3 trials per view (anterior, lateral, posterior)

**COMPLETING THE EVALUATION**

- Using the recommended view, watch the pitcher frame by frame for 3 or more trials per variable, before making a judgment.
- Distinguish between the movement of clothing and that of joints or body segments.
- Check one box only per section.
- Ideal mechanics are shown in italics.
- Explanatory medical notes are provided, marked with ⓘ
- Comments and recommendations can be made on the Summary page.

# PITCHING MECHANICS CHECKLIST

**(I) PREPARATION**

1) Initial Movements - Windup:
- ☐ *The pitcher takes a small step back. The hips and shoulders turn 90 degrees to the target as the pivot foot is aligned with the rubber.*
- ☐ The initial movements cause the pitcher to be unbalanced.
- ☐ The head does not remain positioned over the pivot foot.

ⓘ Instability and lack of rhythm in the pivot causes unreliable pitch location and poor transfer of force from the lower body to the arm.

2) Balance Position
- ☐ *The pitcher is balanced at maximum knee-lift: the trunk is upright over a slightly flexed rear knee, the head is over the rear knee and has not travelled toward home-plate before the stride knee descends.*
- ☐ The pitcher's lower body moves prematurely toward home-plate.
- ☐ The pitcher leans backwards or toward second base during knee-lift.

ⓘ Premature movement toward the plate causes the stride hip to open early. Inappropriate lean indicates incorrect position of the hands, or excessive flexion of the support knee.

3) Hand Separation
- ☐ *From a position close to the chest, the hands move apart only as the stride hip moves towards the target. The throwing hand breaks from the glove in a downward, backward and upward motion. Fingers remain on top of the ball.*
- ☐ The hands separate early and disrupt smooth down-back-up movement.
- ☐ The hands separate late and disrupt smooth down-back-up movement.

ⓘ Excessive arm swing behind the body increases stress on the shoulder during arm cocking. Insufficient downward/backward movement affects the position of the arm at foot contact. The throwing hand should break down and back before moving rapidly up so that the upper arm is horizontal and the hand

**(II) STRIDE**

4. Movement of Stride Hip
- ☐ *The stride leg descends directly toward the target. The lateral aspect of the lead hip faces the plate until just before foot contact.*
- ☐ The stride leg is flexed but placed down close to the pitcher's support leg as the hands separate.
- ☐ The stride leg is flexed but swings open as the foot begins downward movement.

ⓘ As the hands move apart, the lateral hip and heel of the stride leg move toward the batter, ensuring hip rotation does not occur prematurely and leave the arm behind at foot contact.

5) Stride Length
- ☐ *The pitcher lands on the ball of the foot. Measured from the rubber to the front ankle, the stride length is 80-90% of the pitcher's height.*
- ☐ Stride length is substantially less than the pitcher's height. The head is positioned toward the front foot.
- ☐ Stride length exceeds the pitcher's height. The back foot pulls off the rubber.

ⓘ Stride length significantly affects the motion of the trunk - incorrect stride length may cause the body weight to prematurely move forward, or block hip rotation and the use of the trunk to propel the ball forward.

6) Knee Flexion and Weight Distribution at foot contact
- ☐ *The angle behind the stride knee is 120-145 degrees when the stride foot makes full contact with the mound. The head forms an even triangle with the feet.*
- ☐ The stride knee is too straight. The head has moved too far forward.
- ☐ The stride knee is too flexed.

ⓘ A semi-flexed knee at contact allows rotation of the hips without dissipating the energy generated by wind up through blocking hip rotation or causing...

**(IIa) FOOT PLACEMENT**

7) Stride Offset
- ☐ *The stride foot is grounded within 10cm (4 inches) of an imaginary line from the instep of the pivot foot to home plate.*
- ☐ The stride is too closed (foot placed across the body/toward third base for a right-handed pitcher RHP)
- ☐ The stride is too open (placed toward first base for RHP)

ⓘ If the stride offset is open, the hips have prematurely rotated toward the target and left the arm behind, increasing stress on the shoulder as the trunk rotates. An excessively closed offset does not permit complete hip rotation to assist the arm during acceleration.

8.Foot Angle at Contact
- ☐ *The toes of the stride foot (when in complete contact with the mound) are rotated slightly inward.*
- ☐ The front foot angle is too closed (turned toward third base RHP)
- ☐ The front foot angle is too open (turned toward first base RHP)

ⓘ Open angle of the lead foot indicates the pitcher's hips have prematurely rotated towards the target. A closed foot angle compromises hip rotation.

**(III) ARM PATH**

9. Arm Cocking
- ☐ *The throwing hand breaks from the glove and moves down, back and up into a cocked position the shoulder.*
- ☐ The hand moves back and up without moving down
- ☐ The hand swings back too far behind the pitcher's body.

ⓘ The "down" movement of the hand coordinates the arm with the motion of the stride hip so the arm is correctly placed at foot contact and during trunk rotation. Excessive arm swing behind the body creates stress at the shoulder and elbow as the trunk rotates and rapidly reverses the direction of trunk travel.

10) Arm Position at Foot Contact:
- ☐ *The throwing arm is level with, or slightly behind the body. The throwing hand is directed to shortstop (RHP), forearm is vertical and fingers are on top of the ball.*
- ☐ The arm does not reach a point directly behind the body and forearm is directed toward the open side.
- ☐ The throwing arm swings significantly behind the body and forearm is directed to the closed side (first base for RHP)

ⓘ Excessive arm swing behind the body creates stress at shoulder and elbow as arm is left behind while the trunk rotates to face the hitter. An inadequate arm path limits the range of motion through which the pitcher can impart force to the ball.

11) Shoulder Abduction at Foot Contact
- ☐ *The throwing elbow is level with the line of the shoulders at foot contact - the abducted arms and the trunk of the pitcher form a "T".*
- ☐ The throwing elbow is below the line of the shoulders.
- ☐ The throwing elbow is significantly higher than the shoulder line.

ⓘ An improperly positioned elbow substantially increases the stress on the throwing shoulder and elbow throughout acceleration. The "T" position provides optimal stability for the rotating arm.

12) Elbow flexion at Foot Contact
- ☐ *The throwing elbow is flexed to approximately 90 degrees as the lead foot contacts the mound.*
- ☐ The throwing elbow is flexed toward the pitcher's head.
- ☐ The throwing elbow is too straight.

ⓘ A straight elbow decreases the ability of the elbow to generate velocity when extending toward ball release. Excessive elbow flexion may cause the arm to "fly open" with great force and cause elbow injury as the trunk rotates.

**(IV) ACCELERATION**
**(IVa) TRUNK MECHANICS**

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13. Timing of Hip/Shoulder Rotation:
- ☐ *The pelvis rotates shortly after the foot is grounded, and rotates toward the target before the shoulders (the front shoulder remains closed to the target until the hips have rotated).*
- ☐ The pelvis rotates toward the target *after* the shoulders.
- ☐ The pelvis and shoulders appear to rotate toward the target *simultaneously*.

ⓘ The shoulders rotating after the hips allows greater energy to be stored. Thus greater angular velocity of the upper trunk can be transferred to the arm.

14) Trunk Arching and Drive:
- ☐ *From the first contact of the stride foot, the trunk is held back. The trunk is hyper-extended as the shoulders rotate toward the hitter.*
- ☐ The trunk remains in a neutral alignment as the shoulders rotate.
- ☐ The weight has moved forward early; the trunk flexes further as shoulders rotate.

ⓘ Holding the trunk back as long as possible allows maximum energy from the hips to be stored and imparted to the arm at ball release. Arching the back pre-stretches the muscles of the abdomen, allowing the trunk to move toward the plate with greater velocity at release.

15) Use of Glove Arm:
- ☐ *The glove is at the level of the non-throwing elbow and pulled back close to the body as the pitcher's shoulders rotate toward the plate.*
- ☐ The glove arm remains extended in front of the pitcher.
- ☐ The glove hand hangs by the pitcher's non-throwing side.

ⓘ By actively moving toward the body, the non-throwing arm contributes to the

**(IVb) ARM MECHANICS**

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16) Maximum Elbow Flexion During Cocking/Acceleration:
- ☐ *The throwing elbow does not flex beyond 70-90 degrees as the upper torso rotates toward the hitter.*
- ☐ The throwing elbow collapses inward toward the pitcher's head.
- ☐ The throwing elbow is too straight.

ⓘ A straighter elbow increases the stress on the joint during acceleration due to a longer level arm. Excessive flexion may jam of the posterior aspect of the elbow if the arm "flies open" during the acceleration phase.

17) Maximum External Rotation:
- ☐ *The forearm is parallel with the ground as the trunk faces the hitter.*
- ☐ The throwing arm does not rotate back far enough.
- ☐ The throwing arm reaches maximum significantly before (or after) the trunk faces the hitter.

ⓘ Sequential opening of the hips and shoulders places the arm in a "laid-back" position prior to elbow extension and ball-release. External rotation stores energy to be imparted to the arm during acceleration, but places high demand on the elbow.

**(V) BALL RELEASE**
**(Va) LOWER BODY MECHANICS**

---

18) Knee Flexion at Ball Release
- ☐ *The stride knee is straighter at ball release than at foot contact (see #6- knee should be about 145 degrees at initial foot contact)*
- ☐ The stride knee is too straight
- ☐ The stride knee is too flexed

ⓘ A relatively straight knee indicates the pitcher may be rushing or using a short stride, which allows his trunk to flex early and forces the stride knee to straighten. A flexed stride knee may indicate the trunk is collapsing forward at ball release.

19) Lateral Trunk Tilt at Ball Release:
☐ *The trunk is tilted approximately 20 degrees toward the non-pitching side.*
☐ The trunk is too upright
☐ The trunk is tilted too far and the chin is not aligned over the stride knee

ⓘ Lateral trunk tilt directs the body and arm in deceleration. Improper lateral tilt can place the arm in a poor position at ball release and during follow-through, and lead to shoulder injury/ decreased control of pitch location.

20) Trunk Flexion at Ball Release
☐ *The trunk is flexed forward approximately 60 degrees at release*
☐ The trunk is too upright
☐ The trunk is too flexed

ⓘ Excessive trunk flexion dissipates the stored energy of the trunk and leaves the arm behind. Insufficient trunk flexion will also stress the arm as the trunk is not transferring the energy from the lower body.

**(Vb) ARM POSITION**

---

21) Trunk-Arm Alignment at Ball Release
☐ *The upper arm is approximately level with the body-line at release*
☐ The arm is too far behind the line of the trunk
☐ The arm is too far ahead of the trunk - the pitcher leads with the elbow.

ⓘ The arm should only be slightly in front of the trunk, allowing for the final whip of the forearm and hand to impart velocity and spin to the ball.

22) Shoulder Abduction at Ball release
☐ The elbow is at, or slightly above, the line of the shoulders at ball release
☐ The elbow is too far below the shoulders
☐ The elbow is too far above the shoulders

ⓘ An excessively high or low elbow at release may damage the shoulder - a high compressive force is generated which may jam, grind or tear internal structures. Location and control of the pitch may also be affected.

23) Elbow Flexion at Ball Release:
☐ *The elbow is flexed approximately 20 degrees as the ball leaves the pitcher's hand.*
☐ The elbow is too flexed
☐ The elbow is straight or hyper-extended

ⓘ A straight elbow (long lever arm) increases stress on the joint as the arm is forcefully rotated at ball release. Excessive flexion increases the stress on the posterior aspect of the joint after ball release as the elbow continues to extend, the posterior elbow may be jammed.

**(VI) DECELERATION**

---

24) Follow-Through
☐ *The trunk is horizontal when the throwing hand is farthest from the trunk. The hand is outside the extended lead leg. The back of the shoulder is visible.*
☐ The trunk is too upright and the hand does not finish outside the leg.
☐ Trunk flexion is poorly directed, and causes the pitcher to overbalance.

ⓘ The continued flexion of the trunk during follow-through allows the large muscles of the trunk and legs to absorb the energy of the arm and protect the posterior shoulder and elbow.
A well-directed follow-through leaves the pitcher

## SUMMARY

Good pitching mechanics can improve performance and reduce the risk of injury. Pitching is a complex motion. The action of the lower body and trunk profoundly influence the position and timing of the arm path. Technical faults and injury are often a result of *combinations* of joint actions. (tick one box only)

# APPENDIX 3: JUSTIFICATION FOR MODIFYING THE PITCHING EVALUATION FORM

| **Appendix 3** | | |
|---|---|---|
| Original Form | Revised Form | Explanation |
| **1) Initial movement - Wind up**<br>Correct:<br>• The pitcher takes a small step back. The hips and shoulders turn 90° to the target as the pivot foot is aligned with the rubber.<br><br>Incorrect:<br>• The initial movement causes the pitcher to be unbalanced.<br>• The head does not remain positioned over the pivot foot. | **1) Head Position during wind up**<br>Correct:<br>• Pitcher's head remained balanced over the pivot foot. | • Needed simplification.<br>• All pitchers turned 90° to the target during the wind up. |
| **2) Balance position**<br>Correct:<br>• The pitcher is balanced at maximum knee-lift: The trunk is upright over a slightly flexed rear knee, the head is over the rear knee and has not traveled toward home-plate.<br><br>Incorrect:<br>• The pitcher's lower body moves prematurely toward home plate.<br>• The pitchers lean backwards or toward second base during knee-lift. | **2) Lower extremity movement at max knee-lift**<br>Correct:<br>• Pitcher's lower body (hips) remains over the pivot foot (has not traveled toward home plate) until the stride knee starts to descent.<br><br>**3) Stance knee bending angle at max knee-lift**<br>Correct:<br>• Pitcher's knee is slightly bent.<br><br>Incorrect:<br>• Pitcher's stance knee is too straight.<br>• Pitcher's stance knee is too bent. | • The item was separated into the timing of lower extremity movement relative to max knee-lift (2), and knee flexion angle at max knee-lift (3). |

| Original Form | Revised Form | Explanation |
|---|---|---|
| **3) Hand Separation**<br>Correct:<br>• From a position close to the chest, the hands move apart only as the stride hip moves toward the target. The throwing hand breaks from the glove in a downward, backward, and upward motion. Fingers remain on top of the ball.<br><br>Incorrect:<br>• The hands separate early and disrupt smooth down-back movement.<br>• The hand separate late and disrupt smooth down-back movement. | **4) Timing of hand separation**<br>Correct:<br>• Hand separation occurs at the stride hip moves toward the target.<br><br>Incorrect:<br>• Hand separation occur too early.<br>• Hand separation occur too late.<br><br>**5) Hand/finger position**<br>Correct:<br>• Fingers remain on top of the ball. | • The item was separated into the timing of hand separation (4) and the position of the fingers on the ball (5). |
| **4) Movement of stride hip**<br>Correct:<br>• The stride leg descends directly toward the target. The lateral aspect of the lead hip faces the plate until just before foot contact.<br><br>Incorrect:<br>• The stride leg is flexed, but placed down close to the pitcher's support leg as the hands separate.<br>• The stride leg is flexed by swings open as the foot begins downward movement. | **6) Stride hip movement**<br>Correct:<br>• Lateral aspect of the lead hip faces the plate until just before foot contact. | • Simplified |

| Original Form | Revised Form | Explanation |
|---|---|---|
| **5) Stride length**<br>Correct:<br>• The pitcher lands on the ball of the foot. Measured from the rubber to the front ankle, the stride length is 80-90% if the pitcher's height.<br><br>Incorrect:<br>• Stride length is substantially less than pitcher's height.<br>• Stride length exceeds the pitcher's height. The back foot pulls off the rubber. | **14) Stride length**<br>Correct:<br>• The stride length is 80-90% of the pitcher's height.<br><br>Incorrect:<br>• Stride length is substantially less than pitcher's height.<br>• Stride length exceeds the pitcher's height. The back foot pulls off the rubber. | • Simplified |
| **6) Knee flexion and weight distribution at foot contact**<br>Correct:<br>• The angle behind the stride knee is 120-145° when the stride foot makes full contact with the mound. The head forms an even triangle with the feet.<br><br>Incorrect:<br>• The stride knee is too straight. The head has moved too far forward.<br>• The stride knee is too flexed. | **12) Weight distribution (head position) at foot contact**<br>Correct:<br>• Head forms an even triangle with the feet.<br><br>**13) Stride knee flexion at foot contact**<br>Correct:<br>• The angle behind the stride knee is 120-145° when the stride foot makes full contact with the mound.<br><br>Incorrect:<br>• Stride knee is too straight.<br>• Stride knee is too flexed. | • The item was separated into the weight distribution (head position) (12) and the stride knee flexion angle at foot contact (13). |

| Original Form | Revised Form | Explanation |
|---|---|---|
| **8) Foot angle at contact**<br>Correct:<br>• The toes of the stride foot (when in complete contact with the mound) are rotated slightly inward.<br><br>Incorrect:<br>• The front foot angle is too closed.<br>• The front foot angle is too open. | **16) Foot angle at contact**<br>Correct:<br>• The toes of the stride foot (when in complete contact with the mound) are rotated slightly inward (about 30 degrees).<br><br>Incorrect:<br>• The front foot angle is too closed.<br>• The front foot angle is too open. | • Added "about 30 degrees" to clarify what "rotated slightly" indicates. |
| **10) Arm position at foot contact**<br>Correct:<br>• The throwing arm is level with, or slightly behind the body. The throwing hand is directed to shortstop (RHP), forearm is vertical and fingers are on top of the ball.<br><br>Incorrect:<br>• The arm does not reach a point directly behind the body and forearm is directed toward the open side.<br>• The throwing arm swings significantly behind the body and forearm is directed to the closed side. | **8) Hand position**<br>Correct:<br>• The throwing hand is directed to shortstop (RHP).<br><br>**9) Forearm position**<br>Correct:<br>• Wrist is positioned above the elbow. | • The item was separated into a hand position (8) and a forearm position (9). In the original form specify that the forearm be vertical. In the revised form pitchers were given a point if their wrist was above the elbow (shoulder in external rotation). |

| Original Form | Revised Form | Explanation |
|---|---|---|
| **13) Timing of hip/shoulder rotation**<br>Correct:<br>• The pelvis rotates shortly after the foot is grounded, and rotates toward the target before the shoulders (the front shoulder remains closed until the hips have rotated).<br><br>Incorrect:<br>• The pelvis rotates towards the target after the shoulders.<br>• The pelvis and shoulders appear to rotate toward the target simultaneously. | **20) Timing of hip/shoulder rotation**<br>Correct:<br>• Pelvis rotation precedes the upper torso rotation. | • Simplified |
| **14) Trunk arching and Drive**<br>Correct:<br>• From the first contact of the stride foot, the trunk is held back. The trunk is hyper-extended as the shoulders rotate toward the hitter.<br><br>Incorrect:<br>• The trunk remains in a neutral alignment as the shoulders rotate.<br>• The weight has moved forward early; the trunk flexes further as shoulders rotate. | **21) Trunk arching**<br>Correct:<br>• Trunk is hyper-extended and upper torso remains vertical as the shoulders rotate toward the hitter. | • Simplified |

| Original Form | Revised Form | Explanation |
|---|---|---|
| **17) Maximal external rotation**<br>Correct:<br>• The forearm is parallel with the ground as the trunk faces the hitter.<br><br>Incorrect:<br>• Throwing arm does not rotate back enough.<br>• Throwing arm reaches maximum external rotation significantly before (or after) the trunk faces the hitter. | **18) Maximum external rotation**<br>Correct:<br>• Forearm become parallel or closed to vertical with the trunk as the pitcher faces the hitter.<br><br>Incorrect:<br>• Forearm is not rotate back enough.<br>• Forearm is rotated too far (<180°).<br><br>**19) Timing of maximal external rotation**<br>Correct:<br>• Maximal external rotation is reached as the trunk faces the hitter.<br><br>Incorrect:<br>• Maximal external rotation is reached before the trunk faces the hitter.<br>• Maximal external rotation is reached after the trunk faces the hitter. | • The item was separated into a degree of maximal shoulder external rotation (18) and the timing of maximal external rotation (19). For the item 18, we evaluated the forearm angle relative to the trunk (anatomical), and not relative to the ground. |

| Original Form | Revised Form | Explanation |
|---|---|---|
| **24) Follow-through**<br>Correct:<br>• The trunk is horizontal when the throwing hand is farthest from the trunk. The hand is outside the extended lead leg. The back of the shoulder is visible.<br><br>Incorrect:<br>• The trunk is too upright and the hand does not finish outside the leg.<br>• Trunk flexion is poorly directed, and causes the pitcher to overbalance. | **29) Trunk follow-through**<br>Correct:<br>• Back of the shoulder is visible.<br><br>**30) Arm follow-through**<br>Correct:<br>• Hand finishes outside the leg. | • The item was separated into trunk and arm follow-through. The part about trunk being horizontal when the throwing hand is farthest from the trunk has been eliminated, since trunk was not close to being horizontal even for the pitchers with highest forward trunk tilt angles at ball release. |

## APPENDIX 4: ESTIMATION OF THE SEGMENT MASS AND LOCATION OF THE CENTER OF MASS

Estimation of the segment mass and location of the center of mass [38]

Hand mass
= 0.029*wrist circumference + 0.075*wrist breadth + 0.031*hand breadth - 0.746 (constant)
($r^2$=.942, Standard error of estimate = 0.02)

Hand center of mass
= 0.657*wrist breadth -0.202*hand circumference + 2.130 (constant)
($r^2$=.958, Standard error of estimate = 0.02)

Forearm mass
= 0.119*wrist circumference + 0.051*forearm circumference - 1.650 (constant)
($r^2$=.920, Standard error of estimate = 0.06)

Forearm center of mass from elbow (radial head)
= 0.440*forearm length - 0.761*wrist breadth - 5.645 (constant)
($r^2$=.821, Standard error of estimate = 0.51)

Arm mass
= 0.007*body mass + 0.092*Arm circumference + 0.050*Arm length - 3.101 (constant)
($r^2$=.961, Standard error of estimate = 0.09)

Arm center of mass from acromion
= 0.329*Arm length - 0.250*Arm circumference + 2.827*Elbow breadth - 6.168 (constant)
($r^2$=.918, Standard error of estimate = 0.72)

## APPENDIX 5: ESTIMATION OF THE RADIUS OF GYRATION ABOUT THE SEGMENT CENTER OF MASS

| **Estimation of the radius of gyration about the center of mass** [47] | | |
|---|---|---|
| Segment | Definition | Radius of Gyration/Segment Length about the center of mass |
| Hand | Wrist axis/ Knuckle II middle finger | 0.297 |
| Forearm | Elbow axis/ulnar styloid | 0.303 |
| Upper arm | Glenohumeral axis/elbow axis | 0.322 |

## APPENDIX 6: INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

OFFICE OF HUMAN RESEARCH ETHICS
Medical School Building 52
Mason Farm Road
CB #7097
Chapel Hill, NC 27599-7097
(919) 966-3113
Web site: ohre.unc.edu
https://my.research.unc.edu for IRB status
Federalwide Assurance (FWA) #4801

**To**: Saki Oyama
Allied Health Sciences
CB:8700

**From**: Biomedical IRB

**Approval Date**: 7/06/2011
**Expiration Date of Approval:** 7/04/2012

**RE**: Notice of IRB Approval by Expedited Review (under 45 CFR 46.110)
**Submission Type**: Initial
**Expedited Category**: 4.Noninvasive clinical data
**Study #:** 11-1193

**Study Title**: Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers

This submission has been approved by the above IRB for the period indicated. It has been determined that the risk involved in this research is no more than minimal.

**Study Description:**

Purpose: The purpose of this study is to (1) determine whether each of the 5 technical errors at the trunk are associated with increased joint loading, decreased performance, and decreased quality of the pitching technique in adolescent pitchers, (2) whether the number of technical errors are correlated with the joint loading, performance, and quality of the pitching technique, and to (3) examine the effects of providing a technical instruction to pitch with proper trunk movement using the video feedback on joint loading, performance, and quality of the pitching technique in adolescent pitchers who demonstrate at least 1 of the 5 common technical errors. Participants: 60 healthy male adolescent (13-19 years old) pitchers will be recruited for this study. Procedures: All pitchers will be fitted with reflective markers and perform 5 pitches or until achieving 3 strike pitches. The pitcher will be randomly assigned to an experimental or a control group. Pitchers in both groups will perform 3 sets of 5 pitches, during which the pitchers in the experimental group will receive technical instruction and video feedback on the proper pitching mechanics. Pitchers in the control group will continue to pitch as they normally do. After the intervention, the pitchers in both groups will perform 5 pitches or until achieving 3 strike pitches.

**Regulatory and other findings:**

This research, which involves children, meets criteria at 45 CFR 46.404 and/or 21 CFR 50.51 (research involving no greater than minimal risk). Permission of one parent or guardian is sufficient.

**Investigator's Responsibilities:**

Federal regulations require that all research be reviewed at least annually. It is the Principal Investigator's responsibility to submit for renewal and obtain approval before the expiration date. You may not continue any research activity beyond the expiration date without IRB approval. Failure to receive approval for continuation before the expiration date will result in automatic termination of the approval for this study on the expiration date.

**IF YOU SUBMITTED ON PAPER,** enclosed are stamped copies of approved consent documents and other recruitment materials (when applicable). You must copy the stamped consent forms for use with subjects unless you have approval to do otherwise. **IF YOU SUBMITTED ONLINE (Behavioral and Public Health-Nursing IRBs Only),** your approved consent forms and other documents are available online at http://apps.research.unc.edu.

You are required to obtain IRB approval for any changes to any aspect of this study before they can be implemented (use the modification form at ohre.unc.edu/forms). Any unanticipated problem involving risks to subjects or others (including adverse events reportable under UNC-Chapel Hill policy) should be reported to the IRB using the web portal at https://irbis.unc.edu/irb.

Researchers are reminded that additional approvals may be needed from relevant "gatekeepers" to access subjects (e.g., principals, facility directors, healthcare system).

This study was reviewed in accordance with federal regulations governing human subjects research, including those found at 45 CFR 46 (Common Rule), 45 CFR 164 (HIPAA), 21 CFR 50 & 56 (FDA), and 40 CFR 26 (EPA), where applicable.

CC:
Joseph Myers, Exercise And Sport Science
Cindy Atkins, (Exercise and Sports Science), Non-IRB Review Contact

## APPENDIX 7:DATA USE AGREEMENT FORM (PHOTOGRAPH RELEASE)

Data use agreement

If over 18 years of age;

I, _____ will give permission to the investigators of the study entitled ”Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers “ to use video and/or pictures from my data collection session to be used in conference presentations and/or in manuscript figures.

_____ _____

Signature Date

If under 17 years of age;

I, _____ will give permission to the investigators of the study entitled ”Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers “ to use video and/or pictures from my son’s data collection session to be used in conference presentations and/or in manuscript figures.

_____ _____

Parent Signature Date

# APPENDIX 8: INFORMED CONSENT FORMS

THIS CONSENT DOCUMENT SHOULD BE USED ONLY BETWEEN 7/06/11 AND 7/04/12 APPROVED BY INSTITUTIONAL REVIEW BOARD, UNC-CHAPEL HILL

**University of North Carolina-Chapel Hill**
**Parental Permission for a Minor Child to Participate in a Research Study (Biomedical)**

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**IRB Study #** 11-1193
**Consent Form Version Date:** 6/14/2011

**Title of Study:** Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers

**Principal Investigator:** Sakiko Oyama, MS, ATC
**UNC-Chapel Hill Department:** Exercise and Sports Science
**UNC-Chapel Hill Phone number:** 919-962-7187
**Email Address:** oyamas@email.unc.edu
**Co-Investigators:** Elizabeth Hibberd, MA, ATC
**Faculty Advisor:** Joseph B. Myers, PhD, ATC
**Funding Source and/or Sponsor:** N/A

**Study Contact telephone number:** 919-962-7187
**Study Contact email:** oyamas@email.unc.edu

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**What are some general things you and your child should know about research studies?**
You are being asked to allow your child to take part in a research study. To join the study is voluntary. You may refuse to give permission, or you may withdraw your permission for your child to be in the study, for any reason.

Research studies are designed to obtain new knowledge that may help other people in the future. Your child may not receive any direct benefit from being in the research study. There also may be risks to being in research studies.

Deciding not to be in the study or leaving the study before it is done will not affect your or your child's relationship with the researcher, with the health care provider, or with the University of North Carolina-Chapel Hill. If your child is a patient with an illness, your child does not have to be in the research study in order to receive health care.

Details about this study are discussed below. It is important that you and your child understand this information so that you and your child can make an informed choice about being in this research study. You will be given a copy of this permission form. You and your child should ask the researchers named above, or staff members who may assist them, any questions you or your child have about this study at any time.

**What is the purpose of this study?**
Shoulder and elbow injuries are common among adolescent pitchers. Faulty pitching mechanics that places additional stress on the shoulder and elbow joints are considered one of the reasons why some pitchers get injured. There are many movement patterns in pitching the baseball

coaches consider a technical error that limits the pitchers' performance and increase the stress placed on the joints, and predispose the pitchers to injuries. It is important to study whether these technical errors are in fact linked to joint stress, performance, and quality of your pitching technique. In addition, studying the effects of instructions using the video feedback on how to pitch with proper technique on joint stress, performance, and quality of the pitching mechanics can help us determine whether the instruction can be used to decrease pitcher's risk of getting injured.

The purpose of this research study is to learn about 1) the effects of common technical errors during pitching on the stress experienced at the shoulder and elbow joints, performance, and quality of the pitching mechanics, and 2) effects of instructions and feedback using the video recording on the stress experienced at the shoulder and elbow joints, trunk and arm movement, performance, and quality of the pitching mechanics.

Your son is being asked to be in the study because he is a baseball pitcher between the age of 13-19, who has been pitching for at least 2 seasons.

**Are there any reasons your child should not be in this study?**
Your son should not be in this study if he is 1) an underarm or sidearm pitchers, 2) has any on-going injury/pain/muscle soreness that keeps them from pitching as they normally would, or 3) unwilling to follow the pitching instruction provided by the researcher.

**How many people will take part in this study?**
If your child is in this study, he will be one of approximately 60 people in this research study.

**How long will your child's part in this study last?**
Your son's participation in this study will last approximately 60 minutes. There will be no follow ups for this study.

**What will happen if your child takes part in the study?**
***Testing Preparation***
Prior to participation, you will read and sign the informed consent form approved by the University Institutional Review Board (this form). Your son will read and sign the assent form. After the consent/assent, your son will change into tight-fitting shorts and non-sleeve shirt (ex. spandex). Your son may bring his own or wear the ones provided by the research laboratory. Your son will then fill out a questionnaire regarding his age, limb dominance, years of experience, and injury history. After he completes the questionnaire, we will take measurement of his height, weight, and length, width, and circumference of his dominant-side arm and forearm.

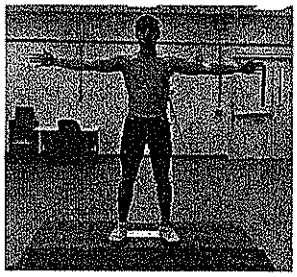
**Figure 1**. Marker set up

Your son will then proceed to warm-up as he normally would before the practices/games (ex. jog, stretch, warm up throws etc.). Once he complete the warm up, 40 markers will be attached onto the his body using the double-sided tape, pre-wrap and the elastic self-adherent tape (**Figure 1**). Once he is fitted with the markers, he will stand with his feet shoulder-width apart and arm at a shoulder height while keeping the elbow straight and palms facing forward for 5

seconds. After the trial, 6 markers will be removed. Your son will then perform 5-10 submaximal throws/pitches to get used to pitching with the reflective markers attached to the body.

***Baseline Pitching Trial***

Once your son is ready to pitch, he will perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis. Your son will pitch from a wind up as fast and as accurate as possible while aiming at the center of the strike zone on the backstop placed at a distance of 60 feet 6 inches (normal pitching distance). Your son's pitching trials will be captured using the motion capture system, force plate (device that records how hard he pushes down with his feet) and the high-speed video cameras. In addition, ball velocity will be measured using a radar gun, and whether or not he ball hit the strike zone will be recorded. Your son will be given 30-60 second rest in between trials. After the baseline trial, your son will be randomized into an experimental or control group by drawing a piece of paper with numbers 1-10. Your son will be randomly assigned to an experimental vs. control group based on the number he picked. *Your son has a 50/50 chance of being assigned to an experimental vs. control group.*

***Practice Intervention using Video Feedback and Instruction***

*If your son is assigned to the experimental group*:

Your son will review the video footage from the fastest strike pitch (front and side views). After playing the videos, the researcher will ask your son to analyze his pitching technique by asking five questions about his technique. After he analyzed his pitching technique, the investigator will go over the parameters he analyzed, and provide instructions to correct the parameter(s) that he did not perform correctly.

After receiving the technical instruction and the videotape feedback, your son will perform 3 sets of 5 practice pitches while attempting to achieve the proper trunk movement. Your son will re-analyze his technique between sets using the video footage of the fastest strike pitch from the previous set of practice trials. If no strike pitches were made, the fastest pitch that was the closest to the strike zone will be used for the video feedback. Before each practice set, your son will be reminded to focus on achieving the proper movement while pitching as fast and as accurate as possible at a target.

After the 3rd practice set, your son will re-analyze the video from the 3rd practice set, and then perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis.

*If your son is assigned to the control group*:

Your son will perform 3 sets of 5 pitches with 5-minute break in between sets without any technical instruction or visual feedback. After the 3rd practice set, your son will wait 5-minute, and perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis.

The completion of the post-intervention testing trial concludes the testing procedure.

**What are the possible benefits from being in this study?**

Research is designed to benefit society by gaining new knowledge. Your child will not benefit personally from being in this research study.

**What are the possible risks or discomforts involved with being in this study?**
The risk of injury associated with pitching in the study is no greater than what is associated with pitching in practice/game situations. There is a slight chance that your son experience mild soreness after pitching. The soreness is comparable to the soreness experienced after pitching in practice/games, and is not injurious in nature. However, there may be uncommon or previously unknown risks that might occur. Your son should report any problems to the researchers.

There is also a slight risk of breach of confidentiality associated with this study. The investigator will minimize this risk by storing the data securely, and making them available only to the researchers involved in this study. All researchers are educated on the importance of protecting your confidentiality through training at the University of North Carolina at Chapel Hill.

**How will your child's privacy be protected?**
No subjects will be identified in any report or publication about this study. Although every effort will be made to keep research records private, there may be times when federal or state law requires the disclosure of such records, including personal information. This is very unlikely, but if disclosure is ever required, UNC-Chapel Hill will take steps allowable by law to protect the privacy of personal information. In some cases, your child's information in this research study could be reviewed by representatives of the University, research sponsors, or government agencies for purposes such as quality control or safety.

Electronic file of your son's pitching mechanics will be stored on the secure laboratory computer indefinitely in case we would like to analyze them in the future.

**What will happen if your child is injured by this research?**
All research involves a chance that something bad might happen. This may include the risk of personal injury. In spite of all safety measures, your child might develop a reaction or injury from being in this study. If such problems occur, the researchers will help your child get medical care, but any costs for the medical care will be billed to you and/or your insurance company. The University of North Carolina at Chapel Hill has not set aside funds to pay you for any such reactions or injuries, or for the related medical care. However, by signing this form, you and your child do not give up any of your legal rights.

**What if you or your child wants to stop before your child's part in the study is complete?**
You can withdraw your child from this study at any time, without penalty. The investigators also have the right to stop your child's participation at any time.

**Will your child receive anything for being in this study?**
Your child will be receiving a CD with video footages of your pitching trials for participating in this study. The CD will be mailed to you following the study.

**Will it cost you anything for your child to be in this study?**
It will not cost anything to be in this study.

**What if you are a UNC student?**

You may choose not to give permission for your child to be in the study or to stop being in the study before it is over at any time. This will not affect your class standing or grades at UNC-Chapel Hill. You will not be offered or receive any special consideration if your child takes part in this research.

### What if you are a UNC employee?

Your child's taking part in this research is not a part of your University duties, and refusing to give permission will not affect your job. You will not be offered or receive any special job-related consideration if your child takes part in this research.

### What if you or your child has questions about this study?

You and your child have the right to ask, and have answered, any questions you may have about this research. If there are questions, complaints, concerns, or if a research-related injury occurs, you should contact the researchers listed on the first page of this form.

### What if you or your child has questions about his/her rights as a research subject?

All research on human volunteers is reviewed by a committee that works to protect your rights and welfare. If you or your child has questions or concerns about your child's rights as a research subject, or if you would like to obtain information or offer input, you may contact the Institutional Review Board at 919-966-3113 or by email to IRB_subjects@unc.edu.

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**Title of Study:** Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers

**Principal Investigator:** Sakiko Oyama, MS, ATC

### Parent's Agreement:

I have read the information provided above. I have asked all the questions I have at this time. I voluntarily give permission to allow my child to participate in this research study.

________________________________________
Printed Name of Research Subject (Child)

________________________________________ ______________
Signature of Parent Date

________________________________________
Printed Name of Parent

________________________________________ ______________
Signature of Research Team Member Obtaining Permission Date

________________________________________
Printed Name of Research Team Member Obtaining Permission

**University of North Carolina-Chapel Hill**
**Consent to Participate in a Research Study**
**Adult Subjects**
**Biomedical Form**

THIS CONSENT DOCUMENT SHOULD BE USED ONLY BETWEEN 7/06/11 AND 7/04/12 APPROVED BY INSTITUTIONAL REVIEW BOARD, UNC-CHAPEL HILL

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**IRB Study #** 11-1193
**Consent Form Version Date:** 6/14/2011

**Title of Study:** Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers

**Principal Investigator:** Sakiko Oyama, MS, ATC
**UNC-Chapel Hill Department:** Exercise and Sports Science
**UNC-Chapel Hill Phone number:** 919-962-7187
**Email Address:** oyamas@email.unc.edu
**Co-Investigators:** Elizabeth Hibberd, MA, ATC
**Faculty Advisor:** Joseph B. Myers, PhD, ATC
**Funding Source and/or Sponsor:** N/A

**Study Contact telephone number:** 919-962-7187
**Study Contact email:** oyamas@email.unc.edu

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**What are some general things you should know about research studies?**
You are being asked to take part in a research study. To join the study is voluntary. You may refuse to join, or you may withdraw your consent to be in the study, for any reason.

Research studies are designed to obtain new knowledge that may help other people in the future. You may not receive any direct benefit from being in the research study. There also may be risks to being in research studies.

Deciding not to be in the study or leaving the study before it is done will not affect your relationship with the researcher, your health care provider, or the University of North Carolina-Chapel Hill. If you are a patient with an illness, you do not have to be in the research study in order to receive health care.

Details about this study are discussed below. It is important that you understand this information so that you can make an informed choice about being in this research study. You will be given a copy of this consent form. You should ask the researchers named above, or staff members who may assist them, any questions you have about this study at any time.

**What is the purpose of this study?**
Shoulder and elbow injuries are common among adolescent pitchers. Faulty pitching mechanics that places additional stress on the shoulder and elbow joints are considered one of the reasons why some pitchers get injured. There are many movement patterns in pitching the baseball

coaches consider a technical error that limits the pitchers' performance and increase the stress placed on the joints, and predispose the pitchers to injuries. It is important to study whether these technical errors are in fact linked to joint stress, performance, and quality of your pitching technique. In addition, studying the effects of instructions using the video feedback on how to pitch with proper technique on joint stress, performance, and quality of the pitching mechanics can help us determine whether the instruction can be used to decrease pitcher's risk of getting injured.

The purpose of this research study is to learn about 1) the effects of common technical errors during pitching on the stress experienced at the shoulder and elbow joints, performance, and quality of the pitching mechanics, and 2) effects of instructions and feedback using the video recording on the stress experienced at the shoulder and elbow joints, trunk and arm movement, performance, and quality of the pitching mechanics.

You are being asked to be in the study because you are a baseball pitcher between the age of 13-19, who has been pitching for at least 2 seasons.

**Are there any reasons you should not be in this study?**
You should not be in this study if you are 1) an underarm or sidearm pitchers, 2) have any on-going injury/pain/muscle soreness that keeps them from pitching as they normally would, or 3) unwilling to follow the pitching instruction provided by the researcher.

**How many people will take part in this study?**
If you decide to be in this study, you will be one of approximately 60 people in this research study. There will be no follow ups for this study.

**How long will your part in this study last?**
Your participation in this study will last approximately 60 minutes.

**What will happen if you take part in the study?**

***Testing Preparation***
Prior to participation, you will read and sign the informed consent form approved by the University Institutional Review Board (this form). After the consent, you will change into tight-fitting shorts and non-sleeve shirt (ex. spandex). You may bring your own or wear the ones provided by the research laboratory. You will then fill out a questionnaire regarding your age, limb dominance, years of experience, and injury history. After you complete the questionnaire, we will take measurement of your height, weight, and length, width, and circumference of your dominant side arm and forearm.

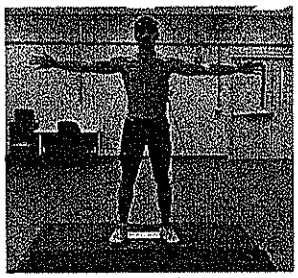
**Figure 1**. Marker set up

You will then proceed to warm-up as you normally would before the practices/games (ex. jog, stretch, warm up throws etc.). Once you complete the warm up, 40 markers will be attached onto your body using the double-sided tape, pre-wrap and the elastic self-adherent tape (**Figure 1**). Once you are fitted with the markers, you will stand with your feet shoulder-width apart and arm straight at a shoulder height with palms facing forward for 5 seconds. After the trial, 6

markers will be removed. You will then perform 5-10 submaximal throws/pitches to get used to pitching with the reflective markers attached to the body.

***Baseline Pitching Trial***

Once you are ready, you will perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis. You will pitch from a wind up as fast and as accurate as possible while aiming at the center of the strike zone on the backstop placed at a distance of 60 feet 6 inches (normal pitching distance). Your pitching trials will be captured using the motion capture system, force plate(device that records how hard your are pushing down with your feet) and the high-speed video cameras. In addition, ball velocity will be measured using a radar gun, and whether or not he ball hit the strike zone will be recorded. You will be given 30-60 second rest in between trials. After the baseline trial, you will be randomized by drawing a piece of paper with numbers 1-10. You will be randomly assigned to an experimental vs. control group based on the number you picked. *You have a 50/50 chance of being assigned to an experimental vs. control group.*

***Practice Intervention using Video Feedback and Instruction***

*If you are assigned to the experimental group*:

You will review the video footage from the fastest strike pitch (front and side views). After playing the videos, the researcher will ask you to analyze your pitching technique by asking five questions about your technique. After you analyze your pitching technique, the investigator will go over the parameters you analyzed, and provide instructions to correct the parameter(s) that you did not perform correctly.

After receiving the technical instruction and the videotape feedback, you will perform 3 sets of 5 practice pitches while attempting to achieve the proper trunk movement. You will re-analyze your technique between sets using the video footage of the fastest strike pitch from the previous set of practice trials. If no strike pitches were made, the fastest pitch that was the closest to the strike zone will be used for the video feedback. Before each practice set, you will be reminded to focus on achieving the proper movement while pitching as fast and as accurate as possible at a target.

After the 3rd set of practice pitch, you will re-analyze the video from the 3rd practice set, and then perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis.

*If you are assigned to the control group*:

You will perform 3 sets of 5 pitches with 5-minute break in between sets without any technical instruction or visual feedback. After the 3rd set of practice pitch, you wait 5 minutes and perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis.

The completion of the post-intervention testing trial concludes the testing procedure for the pitchers.

**What are the possible benefits from being in this study?**
Research is designed to benefit society by gaining new knowledge. You will not benefit personally from being in this research study.

**What are the possible risks or discomforts involved with being in this study?**
The risk of injury associated with pitching in the study is no greater than what is associated with pitching in practice/game situations. There is a slight chance that you experience mild soreness after pitching. The soreness is comparable to the soreness experienced after pitching in practice/games, and is not injurious in nature. However, there may be uncommon or previously unknown risks that might occur. You should report any problems to the researchers.

There is also a slight risk of breach of confidentiality associated with this study. The investigator will minimize this risk by storing the data securely, and making them available only to the researchers involved in this study. All researchers are educated on the importance of protecting your confidentiality through training at the University of North Carolina at Chapel Hill.

**How will your privacy be protected?**
No subjects will be identified in any report or publication about this study. Although every effort will be made to keep research records private, there may be times when federal or state law requires the disclosure of such records, including personal information. This is very unlikely, but if disclosure is ever required, UNC-Chapel Hill will take steps allowable by law to protect the privacy of personal information. In some cases, your information in this research study could be reviewed by representatives of the University, research sponsors, or government agencies for purposes such as quality control or safety.

Electronic file of your pitching mechanics will be stored on the secure laboratory computer indefinitely in case we would like to analyze them in the future.

**What will happen if you are injured by this research?**
All research involves a chance that something bad might happen to you. This may include the risk of personal injury. In spite of all safety measures, you might develop a reaction or injury from being in this study. If such problems occur, the researchers will help you get medical care, but any costs for the medical care will be billed to you and/or your insurance company. The University of North Carolina at Chapel Hill has not set aside funds to pay you for any such reactions or injuries, or for the related medical care. However, by signing this form, you do not give up any of your legal rights.

**What if you want to stop before your part in the study is complete?**
You can withdraw from this study at any time, without penalty. The investigators also have the right to stop your participation at any time.

**Will you receive anything for being in this study?**
You will be receiving a CD with video footages of your pitching trials for participating in this study. The CD will be mailed to you following the study.

**Will it cost you anything to be in this study?**

Your time will be your only cost in this study.

**What if you have questions about this study?**

You have the right to ask, and have answered, any questions you may have about this research. If you have questions, complaints, concerns, or if a research-related injury occurs, you should contact the researchers listed on the first page of this form.

**What if you have questions about your rights as a research subject?**

All research on human volunteers is reviewed by a committee that works to protect your rights and welfare. If you have questions or concerns about your rights as a research subject, or if you would like to obtain information or offer input, you may contact the Institutional Review Board at 919-966-3113 or by email to IRB_subjects@unc.edu.

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**Title of Study:** Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers

**Principal Investigator:** Sakiko Oyama, MS, ATC

**Subject's Agreement:**

I have read the information provided above. I have asked all the questions I have at this time. I voluntarily agree to participate in this research study.

| | |
|---|---|
| Signature of Research Subject | Date |
| Printed Name of Research Subject | |
| Signature of Research Team Member Obtaining Consent | Date |
| Printed Name of Research Team Member Obtaining Consent | |

**University of North Carolina-Chapel Hill**
**Assent to Participate in a Research Study**
**Adolescent Subjects age 15-17**
**Biomedical Form**

THIS CONSENT DOCUMENT SHOULD BE USED ONLY BETWEEN 7/06/11 AND 7/04/12 APPROVED BY INSTITUTIONAL REVIEW BOARD, UNC-CHAPEL HILL

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**IRB Study #** 11-1193
**Assent Form Version Date:** 6/14/2011

**Title of Study:** Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers

**Principal Investigator:** Sakiko Oyama, MS, ATC
**UNC-Chapel Hill Department:** Exercise and Sports Science
**UNC-Chapel Hill Phone number:** 919-962-7187
**Email Address:** oyamas@email.unc.edu
**Co-Investigators:** Elizabeth Hibberd, MA, ATC
**Faculty Advisor:** Joseph B. Myers, PhD, ATC
**Funding Source and/or Sponsor:** N/A

**Study Contact telephone number:** 919-962-7187
**Study Contact email:** oyamas@email.unc.edu

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**What are some general things you should know about research studies?**

You are being asked to take part in a research study. Your parent, or guardian, needs to give permission for you to be in this study. You do not have to be in this study if you don't want to, even if your parent has already given permission. To join the study is voluntary. You may refuse to join, or you may withdraw your consent to be in the study, for any reason.

Research studies are designed to obtain new knowledge that may help other people in the future. You may not receive any direct benefit from being in the research study. There also may be risks to being in research studies.

Deciding not to be in the study or leaving the study before it is done will not affect your relationship with the researcher, your health care provider, or the University of North Carolina-Chapel Hill. If you are a patient with an illness, you do not have to be in the research study in order to receive health care.

Details about this study are discussed below. It is important that you understand this information so that you can make an informed choice about being in this research study. You will be given a copy of this consent form. You should ask the researchers named above, or staff members who may assist them, any questions you have about this study at any time.

**What is the purpose of this study?**
Shoulder and elbow injuries are common among adolescent pitchers. Poor pitching mechanics that places stress on the shoulder and elbow joints are considered one of the reasons why some pitchers get injured. There are many movement patterns in pitching the baseball coaches consider a poor technique that limits the pitchers' performance and increase the stress placed on the joints, and may cause the pitchers to get injured (technical errors). It is important to study whether these technical errors are in fact related to joint stress, performance, and quality of your pitching technique. In addition, studying how the instructions using the video re-play on how to pitch with proper technique affects the joint stress, performance, and quality of the pitching mechanics can help us determine whether the instruction can be used to decrease pitcher's risk of getting injured.

The purpose of this research study is to learn about 1) the effects of common technical errors during pitching on the stress experienced at the shoulder and elbow joints, performance, and quality of the pitching mechanics, and 2) effects of instructions and feedback using the video recording on the stress experienced at the shoulder and elbow joints, trunk and arm movement, performance, and quality of the pitching mechanics.

You are being asked to be in the study because you are a baseball pitcher between the age of 13-19, who has been pitching for at least 2 seasons.

**Are there any reasons you should not be in this study?**
You should not be in this study if you are 1) an underarm or sidearm pitchers, 2) have any on-going injury/pain/muscle soreness that keeps them from pitching as they normally would, or 3) unwilling to follow the pitching instruction provided by the researcher.

**How many people will take part in this study?**
If you decide to be in this study, you will be one of approximately 60 people in this research study.

**How long will your part in this study last?**
Your participation in this study will last approximately 60 minutes. There will be no follow ups for this study.

**What will happen if you take part in the study?**

***Testing Preparation***
Prior to participation, you will read and sign the informed consent form approved by the University Institutional Review Board (this form). After the consent, you will change into tight-fitting shorts and non-sleeve shirt (ex. spandex). You may bring your own or wear the ones provided by the research laboratory. You will then fill out a questionnaire regarding your age, limb dominance, years of experience, and injury history. After you complete the questionnaire, we will take measurement of your height, weight, and length, width, and circumference of your dominant side arm and forearm.

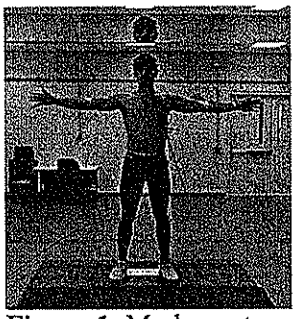
**Figure 1**. Marker set up

You will then proceed to warm-up as you normally would before the practices/games (ex. jog, stretch, warm up throws etc.). Once you complete the warm up, 40 markers will be attached onto your body using the double-sided tape, pre-wrap and the elastic self-adherent tape (**Figure 1**). Once you are fitted with the markers, you will stand with your feet shoulder-width apart and arm at a shoulder height while keeping the elbow straight and palms facing forward for 5 seconds. After the trial, 6 markers will be removed. You will then perform 5-10 submaximal throws/pitches to get used to pitching with the reflective markers attached to the body.

***Baseline Pitching Trial***

Once you are ready, you will perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis. You will pitch from a wind up as fast and as accurate as possible while aiming at the center of the strike zone on the backstop placed at a distance of 60 feet 6 inches (normal pitching distance). Your pitching trials will be captured using the motion capture system, force plate(device that records how hard your are pushing down with your feet) and the high-speed video cameras. In addition, ball velocity will be measured using a radar gun, and whether or not he ball hit the strike zone will be recorded. You will be given 30-60 second rest in between trials. After the baseline trial, you will be randomized by drawing a piece of paper with numbers 1-10. You will be randomly assigned to an experimental vs. control group based on the number you picked. *You have a 50/50 chance of being assigned to an experimental vs. control group.*

***Practice Intervention using Video Feedback and Instruction***

*If you are assigned to the experimental group*:

You will review the video footage from the fastest strike pitch (front and side views). After playing the videos, the researcher will ask you to analyze your pitching technique by asking five questions about your technique. After you analyze your pitching technique, the investigator will go over the parameters you analyzed, and provide instructions to correct the parameter(s) that you did not perform correctly.

After receiving the technical instruction and the videotape replay, you will perform 3 sets of 5 practice pitches while attempting to achieve the proper trunk movement. You will re-analyze your technique between sets using the video footage of the fastest strike pitch from the previous set of practice trials. If no strike pitches were made, the fastest pitch that was the closest to the strike zone will be used for the video replay. Before each practice set, you will be reminded to focus on achieving the proper movement while pitching as fast and as accurate as possible at a target.

After the 3rd set of practice pitch, you will re-analyze the video from the 3rd practice set, and then perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis.

*If you are assigned to the control group*:

You will perform 3 sets of 5 pitches with 5-minute break in between sets without any technical instruction or video replay. After the 3rd set of practice pitch, you wait 5 minutes and perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis.

The completion of the post-intervention testing trial concludes the testing procedure for the pitchers.

**What are the possible benefits from being in this study?**
Research is designed to benefit society by gaining new knowledge. You will not benefit personally from being in this research study.

**What are the possible risks or discomforts involved with being in this study?**
The risk of injury associated with pitching in the study is no greater than what is associated with pitching in practice/game situations. There is a slight chance that you experience mild soreness after pitching. The soreness is comparable to the soreness experienced after pitching in practice/games, and is not injurious in nature. However, there may be uncommon or previously unknown risks that might occur. You should report any problems to the researchers.

There is also a slight risk of breach of confidentiality associated with this study. The investigator will minimize this risk by storing the data securely, and making them available only to the researchers involved in this study. All researchers are educated on the importance of protecting your confidentiality through training at the University of North Carolina at Chapel Hill.

**How will your privacy be protected?**
No subjects will be identified in any report or publication about this study. Although every effort will be made to keep research records private, there may be times when federal or state law requires the disclosure of such records, including personal information. This is very unlikely, but if disclosure is ever required, UNC-Chapel Hill will take steps allowable by law to protect the privacy of personal information. In some cases, your information in this research study could be reviewed by representatives of the University, research sponsors, or government agencies for purposes such as quality control or safety.

Electronic file of your pitching mechanics will be stored on the secure laboratory computer indefinitely in case we would like to analyze them in the future.

**What will happen if you are injured by this research?**
All research involves a chance that something bad might happen to you. This may include the risk of personal injury. In spite of all safety measures, you might develop a reaction or injury from being in this study. If such problems occur, the researchers will help you get medical care, but any costs for the medical care will be billed to you and/or your insurance company. The University of North Carolina at Chapel Hill has not set aside funds to pay you for any such reactions or injuries, or for the related medical care. However, by signing this form, you do not give up any of your legal rights.

**What if you want to stop before your part in the study is complete?**
You can withdraw from this study at any time, without penalty. The investigators also have the right to stop your participation at any time.

**Will you receive anything for being in this study?**

You will be receiving a CD with video footages of your pitching trials for participating in this study. The CD will be mailed to you following the study.

**What if you have questions about this study?**

You have the right to ask, and have answered, any questions you may have about this research. If you have questions, complaints, concerns, or if a research-related injury occurs, you should contact the researchers listed on the first page of this form.

**What if you have questions about your rights as a research subject?**

All research on human volunteers is reviewed by a committee that works to protect your rights and welfare. If you have questions or concerns about your rights as a research subject, or if you would like to obtain information or offer input, you may contact the Institutional Review Board at 919-966-3113 or by email to IRB_subjects@unc.edu.

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**Title of Study:** Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers

**Principal Investigator:** Sakiko Oyama, MS, ATC

**Subject's Agreement:**

I have read the information provided above. I have asked all the questions I have at this time. I voluntarily agree to participate in this research study.

| | |
|---|---|
| Your signature if you agree to be in the study | Date |
| Printed name if you agree to be in the study | |
| Signature of Research Team Member Obtaining Assent | Date |
| Printed Name of Research Team Member Obtaining Assent | |

**University of North Carolina-Chapel Hill**
**Assent to Participate in a Research Study**
**Minor Subjects (7-14 yrs)**

THIS CONSENT DOCUMENT SHOULD BE USED ONLY BETWEEN 7/06/11 AND 7/04/12 APPROVED BY INSTITUTIONAL REVIEW BOARD, UNC-CHAPEL HILL

**IRB Study #** 11-1193
**Consent Form Version Date:** 6/14/2011

**Title of Study:** Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers

**Person in charge of study:** Sakiko Oyama, MS, ATC
**Where they work at UNC-Chapel Hill:** Exercise and Sports Science
**Other people who work on the study:** Elizabeth Hibberd, MA, ATC, Joseph B. Myers, PhD, ATC

**Study contact phone number:** 919-962-7187
**Study contact Email Address:** oyamas@email.unc.edu

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The people named above are doing a research study.

**These are some things we want you to know about research studies:**
Your parent needs to give permission for you to be in this study. You do not have to be in this study if you don't want to, even if your parent has already given permission.

You may stop being in the study at any time. If you decide to stop, no one will be angry or upset with you.

Sometimes good things happen to people who take part in studies, and sometimes things we may not like happen. We will tell you more about these things below.

**Why are they doing this research study?**
The reason for doing this research is to learn about 1) how the common technical errors during pitching affect the stress experienced at the shoulder and elbow joints, performance, and quality of the pitching mechanics, and 2) how the instructions and feedback using the video recording affect the stress experienced at the shoulder and elbow joints, movement pattern, performance, and quality of the pitching mechanics.

**Why are you being asked to be in this research study?**
You are being asked to be in the study because you are a baseball pitcher between the age of 13 and 19, who has been pitching for at least 2 seasons.

**How many people will take part in this study?**
*If* you decide to be in this study, you will be one of about 60 people in this research study.

**What will happen during this study?**
This study will take place at the Sports Medicine Research Laboratory and will last approximately 60 minutes. You will be asked to change into a tight-fitting shorts and sleeveless shirt for this study. We will measure your height, weight, and size of your throwing arm and forearm, and ask you to tell us about your baseball experience and injury history by completing a questionnaire. We will then put a lot of smalls balls called (reflective markers) on your body to track your movement.

Once you are ready, you will perform 5 pitches or until you make 3 strike pitches. We will then assign you to either "experimental" or "control" group. You have 50/50 chance of being assigned into either group.

*If you are assigned to the experimental group*:
You will be asked to review and analyze the video footage from the fastest strike pitch (front and side views). After playing the videos, the researcher will ask you to analyze your pitching technique by asking five questions about your technique. After you analyze your pitching technique, the investigator will go over the parameters you analyzed, and provide instructions to correct the parameter(s) that you did not perform correctly.

After receiving the technical instruction and the videotape replay, you will perform 3 sets of 5 practice pitches while attempting to achieve the proper trunk movement. You will re-analyze your technique between sets using the video footage of the fastest strike pitch from the previous set of practice trials. If no strike pitches were made, the fastest pitch that was the closest to the strike zone will be used for the video replay. Before each practice set, you will be reminded to focus on achieving the proper movement while pitching as fast and as accurate as possible at a target.

After the 3rd set of practice pitch, you will re-analyze the video from the 3rd practice set, and then perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis.

*If you are assigned to the control group*:
You will be asked to perform 3 sets of 5 pitches with 5-minute break in between sets without any technical instruction or video replay. After the 3rd set of practice pitch, you wait 5 minutes and perform a minimum of 5 fast-pitches or until at least 3 strike pitches are captured for analysis.

**Who will be told the things we learn about you in this study?**
Only the researchers working on this project will be told the things we learn about you in this study.

**What are the good things that might happen?**
People may have good things happen to them because they are in research studies. These are called "benefits." You will not benefit from being in this research study.

**What are the bad things that might happen?**
Sometimes things happen to people in research studies that may make them feel bad. These are called "risks." The only risk with this study is that your arms may get sore from pitching. The soreness is similar to what you feel after pitching in practices or games. Not all of these things may happen to you. None of them may happen or things may happen that the researchers don't know about. You should report any problems to the researcher

**Will you get any money or gifts for being in this research study?**
You will receive a CD with video footages of your pitching trials for being in this study.

**Who should you ask if you have any questions?**
If you have questions you should ask the people listed on the first page of this form. If you have other questions, complaints or concerns about your rights while you are in this research study you may contact the Institutional Review Board at 919-966-3113 or by email to IRB_subjects@unc.edu.

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**Title of Study:** Effects of Pitching Mechanics on Joint Loading and Performance in Adolescent Baseball Pitchers

**Principal Investigator:** Sakiko Oyama, MS, ATC

If you sign your name below, it means that you agree to take part in this research study.

_____ _____
Sign your name here if you want to be in the study Date

_____
Print your name here if you want to be in the study

_____ _____
Signature of Research Team Member Obtaining Assent Date

_____
Printed Name of Research Team Member Obtaining Assent

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