Matthew D. Milewski is with the Department of Orthopaedics, Yale University School of Medicine, New Haven, CT. Sylvia Õunpuu and Matthew Solomito are with the Center for Motion Analysis, Connecticut Children's Medical Center, Farmington, CT. Melany Westwell is with Paladin Physical Therapy, Cranston, RI. Carl W. Nissen *(Corresponding Author)* is with Elite Sports Medicine, Connecticut Children' Medical Center, Farmington, CT, and with the Department of Orthopaedics, University of Connecticut Health Center, Farmington, CT.

Adolescent Baseball Pitching Technique: Lower Extremity Biomechanical Analysis

Matthew D. Milewski,[1] Sylvia Õunpuu,[2] Matthew Solomito,[2] Melany Westwell,[3] and Carl W. Nissen[2,4]

[1]Yale University School of Medicine; [2]Connecticut Children's Medical Center; [3]Paladin Physical Therapy; [4]University of Connecticut Health Center

Documentation of the lower extremity motion patterns of adolescent pitchers is an important part of understanding the pitching motion and the implication of lower extremity technique on upper extremity loads, injury and performance. The purpose of this study was to take the initial step in this process by documenting the biomechanics of the lower extremities during the pitching cycle in adolescent pitchers and to compare these findings with the published data for older pitchers. Three-dimensional motion analysis using a comprehensive lower extremity model was used to evaluate the fast ball pitch technique in adolescent pitchers. Thirty-two pitchers with a mean age of 12.4 years (range 10.5–14.7 years) and at least 2 years of experience were included in this study. The pitchers showed a mean of 49 ± 12° of knee flexion of the lead leg at foot contact. They tended to maintain this position through ball release, and then extended their knee during the follow through phase (ball release to maximal internal glenohumeral rotation). The lead leg hip rapidly progressed into adduction and flexion during the arm cocking phase with a range of motion of 40 ± 10° adduction and 30 ± 13° flexion. The lead hip mean peak adduction velocity was 434 ± 83°/s and flexion velocity was 456 ± 156°/s. Simultaneously, the trailing leg hip rapidly extended approaching to a mean peak extension of –8 ± 5° at 39% of the pitch cycle, which is close to passive range of motion constraints. Peak hip abduction of the trailing leg at foot contact was –31 ± 12°, which also approached passive range of motion constraints. Differences and similarities were also noted between the adolescent lower extremity kinematics and adult pitchers; however, a more comprehensive analysis using similar methods is needed for a complete comparison.

Keywords: overhead sports, kinematics, motion analysis, youth sports, throwing

The increase in shoulder and elbow pain and injuries is a well-recognized problem in adolescent pitchers (Adams, 1968, Grana & Rashkin, 1980, Gugenheim et al., 1976, Lyman et al., 2002, 2001). Previous authors and many coaches have suggested that correct pitching mechanics may be the solution to this problem. This has led to a significant increase in biomechanical studies using high-speed three-dimensional motion analysis to better understand both the kinematics and kinetics of adolescent pitching mechanics, injury risk factors, and injury prevention (Davis et al., 2009, Dun et al., 2008[AUQ1], Fleisig et al., 1999, Fortenbaugh et al., 2009, Nissen et al., 2009, Sabick et al., 2004). The majority of these studies has focused on the upper extremity and trunk motions and has led to an improved understanding of the high demands of the pitching motion.

The lower extremity mechanics are also recognized as an integral part of the pitching motion. The important contribution of the lower extremity to overhead athletes and their related motions has been previously described as a kinetic chain in which all body segments are required to move the upper extremity joints into proper positioning to minimize the loads on each segment and pass the generated force from the legs to the more distal segments (Kibler, 1995). The lower extremity and trunk provide the beginning of the kinetic chain that ends with force transmission to the baseball at the time of ball release. The lower extremity has been noted to be important for a stable base from which arm motion can be more efficiently and safely generated along with providing rotational momentum (Burkhart et al., 2003, Kibler, 1991). Weakness or inflexibility in the trailing hip for example has been implicated as a site of a potential break in the kinetic chain during the pitching cycle, which can lead to an increase in lumbar lordosis with the arm trailing the body and resultant "hyperangulation" and increased glenohumeral external rotation (Burkhart et al., 2003, Sisto & Jobe, 1986).

The implications of lower extremity weakness and inflexibility on the kinetic chain have been described, but have not yet been analyzed in terms of three-dimensional motion analysis. Robb et al., however, have begun to look at this question by examining passive hip range of motion for the coronal and transverse planes in professional baseball players and how it relates to a variety of parameters including ball velocity, trunk separation and pelvic motion (Robb et al., 2010). They found increased passive range of motion of the trailing leg hip compared with the lead hip. Robb et al. also found good correlations between the passive range of motion arc in the coronal and transverse planes with ball velocity, stride length, trunk separation velocity and pelvic orientation. They did not, however, include passive hip flexion and extension ranges, and did not report the lower extremity hip kinematics during pitching. Further study of the lower extremity during the pitching cycle would ideally include incorporation of the hip, knee, and foot kinematics of both the lead leg and the trailing leg, as well as passive range of motion peaks in all planes for a more complete understanding of the lower extremities' contribution to pitching mechanics and the implications of limited hip range of motion.

Several studies have begun this effort by evaluating the lower extremity kinematics during the pitching cycle (Davis et al., 2009, Dun et al., 2008[AUQ2], Escamilla et al., 1998, 2007, Matsuo et al., 2001, Robb et al., 2010) and two studies present lower extremity data for youth or adolescent pitchers (Dun et al., 2008[AUQ3], Fleisig et al., 1999). These studies have led to a deeper understanding of lower extremity function in the adolescent athlete through documentation of stride length, lead knee sagittal plane motion and lead foot position and angle (Dun et al., 2008[AUQ4], Fortenbaugh et al., 2009). However, none of these studies include a full lower extremity analysis involving both the lead and trailing legs and hip, knee and ankle joints. Limited lower extremity data for the lead knee at foot contact across ages and experience does not show a trend of increasing or decreasing flexion with increasing age in the published literature.

A more comprehensive lower extremity model including both the lead and trailing limbs is needed to improve our understanding of the lower extremity mechanics during the pitching motion. This would lead to a better understanding of the demands on the hip joint with respect to the end range of motion available at the hip. It would also allow a better understanding of the impact of lower extremity motion on the loads in the upper extremity shoulder, elbow and wrist and to performance such as ball velocity. Since adolescents play baseball and get injured, it is important to understand their upper and lower extremity motion during pitching, and determine how it does or does not differ from older and more experienced pitchers. As the data collection for this study is taking place in an institution that provides care for injured adolescent pitchers as well as high school and college pitchers, knowledge of pitching biomechanics for the younger uninjured pitcher is required. Therefore, the purpose of this study was to add to the current understanding of the lower extremity motion by completing a full lower extremity evaluation during the fastball pitch for adolescent pitchers and comparing these outcomes to more experienced pitchers.

Methods

Subjects

Thirty-two (32) subjects under the age of 15 were recruited from local youth baseball programs. Each pitcher had at least 2 years of pitching experience in organized baseball and no history of arm surgery or current arm pain.

The institutional review board at the Connecticut Children's Medical Center approved the project. All subjects signed assent forms, and informed consent was obtained from their parents before involvement in the study. Of note, study involvement included analysis of both upper and lower extremity mechanics. The upper extremity findings from this study group have been previous reported in the literature (Nissen et al., 2007).

Data Collection

A medical and pitching history was obtained. A physical exam was performed and anthropomorphic measurements including height, weight, leg lengths, and joint diameters were obtained from each subject.

The measurement and computation of the pitching biomechanics has been previously described (Nissen et al., 2007). The subjects wore athletic shorts and sneakers and no shirts. A total of 38 reflective markers aligned to specific body landmarks were attached directly on the skin to minimize movement artifact. The reflective markers were placed bilaterally on the proximal aspect of the space between the second and third metatarsal, medial and lateral malleolus, distal shank, lateral knee, distal thigh, anterior, and posterior superior iliac spine. Additional reflective markers were placed on the trunk, head and bilateral upper extremities as previously described (Nissen et al., 2007). Two markers were placed along the baseball diameter to track the ball velocity and timing of ball release.

Each subject was then given an unlimited amount of time to stretch and throw until adequately warmed up. Subjects pitched from a flat surface (without a mound) in the center of the laboratory toward a net with a designated strike zone 45 feet away. Motion data were collected from a total of 10 fastball pitches with the first three pitches having a complete data set included in the final data analysis.

A motion measurement system (Vicon 512 Motion Systems, Los Angeles, CA) was used to measure motion data. This system used 12 synchronized cameras placed circumferentially around the laboratory. Motion data from the reflective markers was collected at 250-Hz. A fourth-order, zero-lag Butterworth digital filter with a cutoff frequency of 15 Hz was used for smoothing the raw maker trajectories.

Data Analysis

Initial data processing was performed in Workstation (Vicon Motion Systems, Los Angeles, CA) including marker reconstruction, creation of marker trajectories, and generation of kinematics using the model described in Nissen et al. (Nissen et al., 2007). The joint angles were calculated using Euler equations of motion. The rotation sequences used for the lower extremity joints were sagittal, coronal, and transverse (y, x, z) following standard procedures (Davis & Deluca, 1996, Kadaba et al., 1990)

The pitching motion was divided into standard phases as previously described (Fleisig et al., 1995). Data analysis was limited to the arm-cocking phase (lead foot contact to maximum glenohumeral external rotation), arm-acceleration phase (maximum glenohumeral external rotation to ball-release), and arm-deceleration phase (ball release to maximum glenohumeral internal rotation). Lead foot contact was the time when any part of the foot (heel or toe) contacted the ground, as pitchers were found to vary. Ground contact was defined by a velocity of the heel or toe marker of the lead foot that was less than 1.5 m/s. Ball release was defined as the instant when the distance between any of the markers on the baseball and the marker on the hand increased by greater than 2 cm. The pitching cycle from foot contact to maximum glenohumeral internal rotation was time normalized to 100%.

Summary statistics including mean, standard deviation, minimum and maximum values were computed for all lower extremity kinematic and temporal parameters.

Lower Extremity Parameters

Hip motion (coronal, sagittal and transverse planes) and knee motion (sagittal plane) were computed for both the lead and trailing legs using standard angle definitions (Figure 1A–D). Ankle motion (sagittal plane) was computed for the lead leg only (Figure 1E).

\ Insert Figure 1 \

Stride length was measured and defined as the distance between the ankle joint centers at foot contact. Stride length was normalized due to the wide range of height and leg length values and is presented as two separate ratio values (Stride height = Stride Length/stride height, Stride leg length = Stride Length/stride leg length) (Figure 1J).

Foot position was defined as the distance of the lead leg ankle joint center from a line bisecting home plate (Figure 1J). For a right-handed pitcher, a positive foot position describes deviation in lead foot (left foot for the right hand pitcher) contact to the right or toward the third base side of the baseball diamond. Likewise, a negative foot position describes deviation toward the left or first base side of the baseball diamond.

Thigh and shank angles were computed for the lead leg to examine the verticality of these segments to determine whether adolescent pitchers tended to maintain an upright/extended or crouched/flexed lower limb posture. The thigh segment was defined as a line connecting the hip joint center and the knee joint center of the lead leg. Likewise, the shank segment was defined as a line connecting the knee joint center and the ankle joint center. Thigh and shank angles were defined as the angle between the segment and the vertical. Thus, if the thigh segment was parallel with the floor, the thigh angle was equal to 90 degrees. The thigh and shank angles and angular velocities were calculated throughout the pitching cycle (Figure 1G and 1H).

The degree of drop was computed as a percentage of the overall leg length. It was defined as the vertical drop relative to the fully extended leg [1 – (distance from hip joint center to ankle joint center of the lead leg/leg length)]. The degree of drop was calculated throughout the pitching cycle from foot (Figure 1I).

Foot angle was defined as the angle between the long axis of the lead leg foot and a line connecting the pitcher's mound and home plate (Figure 1F). Thus, if the foot of the lead leg for a right handed pitcher was pointing directly toward home plate, the foot angle would equal 0°, toward third base –90° (internal rotation), and toward first base equal +90° (external rotation). We also evaluated the change in foot angle from foot contact to maximum glenohumeral internal rotation, which was measured as the change in foot angle from foot contact to maximum glenohumeral internal rotation.

Results

The mean age for the 32 male patients included in this study was 12.4 years (range 10.5–14.7). The average weight was 51 ± 15 kg (range 29–87). The average height was 157 ± 13 cm (range 133–181) and average leg length was 83 ± 70 cm (range 68–95). The average stride length was 109 ± 15 cm, stride height ratio average was 69 ± 6% (range 50–81%) and stride leg length ratio average was 130 ± 10% (range 100–147%). The lead leg is the left lower extremity for a typical right-handed pitcher. Of the 32 pitchers tested, all but one was right handed.

Kinematics—Hip

Both the lead and trailing hips demonstrated the largest excursions of motion of all the lower extremity joints during the pitching cycle (Figure 2 and 3). The largest ranges of motion were seen in the coronal plane (abduction/adduction) 40 ± 10°, and sagittal planes (flexion/extension) 30 ± 13°. Interestingly, both hips had remarkably similar arcs of motion; however, the location of the motion within the full arc of motion available in the sagittal plane was very different (lead leg approximately 60–90 degrees of flexion versus the trailing leg 0–30 degrees of flexion). The lead hip began in 32 ± 10° of abduction and 64 ± 17° of flexion at foot contact and moved progressively into adduction and more flexion to achieve 4 ± 9° of adduction and 86 ± 15° of flexion by maximum glenohumeral internal rotation. Hip rotation in the transverse plane remained similar throughout the pitch cycle and well within the typical passive range of motion limits. Maximum adduction (434 ± 83°/s) and flexion (456 ± 156°/s) velocities for the lead leg occurred during the arm cocking phase of the pitching cycle, and were significantly less than the maximum velocities demonstrated in the upper extremity (max elbow extension velocity = 1782 ± 245°/s and max glenohumeral internal rotation velocity = 3343 ± 453°/s [Nissen et al., 2007]).

\ Insert Figures 2 and 3 \

The hip of the trailing leg also had similarly large excursions of motion in the coronal (37 ±11°) and sagittal (30 ±11°) planes. Peak hip extension of the trailing leg (–8 ±5°) occurred during the middle of arm cocking phase (34% pitching cycle) and approached anatomical limits (Figure 3).

Kinematics—Knee

The lead knee started in an average of 49 ± 12° of flexion at foot contact and extended throughout the pitching cycle to 34 ± 18° of flexion at maximum glenohumeral internal rotation (Figure 2). Maximum lead knee extension velocity tended to occur during the acceleration phase (between maximum glenohumeral rotation and ball release) and tended to be less than the velocities noted at the hip. The trailing leg knee sagittal motion differed in that it started in less flexion at foot contact (35 ± 22°), progressively extended through maximum glenohumeral external rotation to 24 ± 22° and then moved toward progressive flexion through maximum glenohumeral internal rotation (Figure 3).

Kinematics—Ankle

The ankle remained minimally plantar flexed and the foot slightly internally rotated (rotated slightly toward third base) throughout the pitching cycle (Figure 2 and Table 1). There was minimal pivoting or spinning of the foot after foot contact. The mean change in foot angle from foot contact to maximum glenohumeral internal rotation was 5 ± 6° of external rotation.

\ Insert Table 1 \

The composition and impact of the lead leg knee flexion was evaluated by looking at the lead leg thigh segment angle, shank segment angle, as well as the vertical drop throughout the pitching cycle. The lead leg thigh angle started from an average angle of 57 ± 11° at foot contact and moved toward a slightly more vertical position with an average angle of 46 ± 12° at maximum glenohumeral internal rotation (Table 2). The lead leg shank angle started from an average angle of 21 ± 9° and also moved toward a more vertical angle of 11 ± 8° at maximum glenohumeral external rotation which stayed stable through ball release and maximum glenohumeral internal rotation. The average vertical drop was 39 ± 7% at foot contact and the pitcher moved toward a slightly less crouched position during maximum glenohumeral external rotation through maximum glenohumeral internal rotation (35 ± 8% at maximum glenohumeral external rotation, 34 ± 8% at ball release, and 30 ± 8% at maximum glenohumeral internal rotation).

\ Insert Table 2 \

Discussion

The increase in injuries among adolescent baseball pitchers is well documented. While the injury rate may be a result in an increase in the absolute number of pitches thrown over the course of a season or year, it is possible that biomechanical problems may also contribute to injury in young athletes. The evaluation of the upper extremity, trunk and pelvis has been the primary focus of biomechanical studies of pitching across ages and abilities (Dun et al., 2008[AUQ5], Lyman et al., 2002, Matsuo et al., 2001, Nissen et al., 2007, 2009). Although the lower extremity has been included in a few of these studies (Robb et al., 2010) there is limited understanding of lower extremity biomechanics in pitching at all ages. The pitching motion involves a complex organization and sequencing of movements beginning in the lower extremity as energy is transferred ultimately to the baseball. The purpose of this study was to extend the existing knowledge of the pitching motion in adolescent pitchers to include a comprehensive assessment of the lower extremity and to compare these findings with older pitchers.

It is important to study the excursions of the hip joints during pitching not only for understanding of hip position and motion, but also to determine the ranges of hip motion in relationship to the maximum passive range of motion in all planes. During the pitching motion there is significant asymmetry in hip excursion in relationship to the total arc of motion that will have implications on hip strength and motion demands. This has been investigated—at least rotational motion—in pitcher's hips by Ellenbecker et al. in 2007. They found a difference, especially in external rotation motion of a pitcher's hips in 42% of the 100 pitchers tested. They did not, however, report on the other planes of motion (Ellenbecker et al., 2007). Subsequently passive range-of-motion was reported on by Robb et al. They showed a difference between dominant and nondominant hips but did not comment on hip flexion and extension (Robb et al., 2010).

Hip extension in normals has been reported on in the literature. However, the reports have done a poor job in stabilizing the pelvis in our opinion making the relationship between those reports and our current study's findings difficult (Hoppenfeld, 1976). In our study the largest excursions of joint motion in the lower extremity occurred at the hip joint in the coronal and sagittal planes in both the lead and trailing legs. In the transverse plane minimal motion occurred in both lower extremities and the motion was well within the peak ranges in the transverse plane for passive range of motion. However, peak hip extension of the trailing leg at approximately 39% of the pitch cycle and peak hip abduction of the trailing leg at foot contact are close to the typical maximum range of motion of the hip joint according to the normals tested in our laboratory. In the sagittal plane, limited maximum hip extension may lead to compensatory lordosis as the pelvis is pulled into an anterior tilt to accommodate the forward rotation of the thigh segment. This would begin the change of events leading to the "hyperangulation" and increased glenohumeral external rotation described by Jobe (Sisto & Jobe, 1986). In the coronal plane, limited hip abduction when the same hip is near full extension may result in reduced step length and associated reduction in performance. This is suggested by Robb et al. who found a high correlation between trailing limb passive hip abduction range and stride length ($r = .70$, $p < 003$) (Robb et al., 2010).

Interestingly, Robb et al. have shown that professional pitchers demonstrate differences in side-to-side passive range of motion of the hip for the coronal and transverse planes. This may be consistent with the significantly asymmetrical demands on the hip during the pitching motion as suggested by the kinematics of the hip of the adolescents in this study. It is possible that this asymmetry over time results in bony changes also documented by Robb et al. (2010). Both legs for the pitchers in this study showed peak abduction. The trail leg requires peak abduction during hip extension when passive hip abduction is more limited in comparison with when the hip is flexed. The lead leg requires a similar degree of abduction; however, this takes place when the hip is in 64 ± 17 degrees of flexion. This would suggest that the pitching motion may lead to this passive range of motion asymmetry as documented by Robb et al. (2010). Computation of the lower extremity kinetics and measurement of lower extremity strength will help determine the role of muscle strength in determining hip function in pitching. The data in this study suggests that large excursions in range of motion for both the lead and trailing hips may have implications for pitchers with hip inflexibility and possibly weakness as well. Weakness and inflexibility in the hips have been implicated as a potential area for a break in the kinetic chain in the pitching cycle (Burkhart et al., 2003).

There is only one previous study that documents hip kinematics in pitchers. Lead leg hip flexion at ball release has been noted by Dun et al. (2007) in a group of professional pitchers divided into a younger group (18–20 years old) and older group (older than 27 years old) (Dun et al., 2007). Lead leg hip flexion did not significantly differ in their groups (102.2 ± 5.8° for the younger group and 104.4 ± 7.3° for the older group), but was higher than in our group of adolescent pitchers (90 ± 14°). Differences in hip flexion values between these studies is due in part to differences in hip angle definitions defined by differences in reflective marker placement and skeletal model between the studies. The increased hip flexion at ball release in these other studies may be due in part to reduced knee flexion at the same point in the pitch cycle, but may also be a result of increased anterior pelvic and trunk tilt.

Sagittal plane knee motion also shows significant asymmetry between the lead and trail legs as would be expected based on observation of the pitching motion. Although both knees start the pitching cycle at foot contact in flexion (49 ± 12 degrees for the lead leg and 35 ± 22 degrees for the trailing leg), the trailing leg extends followed by flexion and the lead leg flexes followed by extension. Both knees are flexed throughout the pitch cycle. Lead knee flexion at foot contact in our study group was similar to the adolescents in Fleisig et al. (43 ± 12 degrees) and adolescents in Dun et al. (2008[AUQ6]) (48.5 ± 8.3 degrees), but more than the collegiate pitchers in Fleisig et al. (38 ± 9 degrees) (Dun et al., 2008[AUQ7], Fleisig et al., 1999, 2006) (Table 3). In all of these studies, there was increasing knee extension from foot contact to ball release; however, the adolescents in this study remained in the greatest amount of knee flexion at ball release (41 ± 16 degrees). A preliminary review of the mound versus no mound data collected in the same laboratory, suggests that this increase in knee flexion is due in part to pitching from the flat ground. The mean knee angle at foot contact was 40 ± 15 and at ball release 38 ± 17 degrees which are values very similar to more experienced pitchers at foot contact and in a little more flexion at ball release. Some of the differences between the current study and others in terms of knee kinematics could be explained in that there was considerable variability in the patterns of lead leg sagittal knee motion demonstrated by the adolescent pitchers in this study as well as in other studies. All four of the knee patterns described by Matsuo et al. in a group of collegiate pitchers were observed in the current study in addition to a fifth pattern, not previously described, in which the knee stayed extended throughout the pitching cycle in 3 or 10% of the pitchers (Table 1) (Matsuo et al., 2001). Matsuo pattern A (knee flexion moving toward knee extension at ball release) and pattern C (relative knee flexion throughout the pitching cycle) were observed in 72% of our pitchers. The pitchers most frequently demonstrated a fairly flexed knee (49 ± 12 degrees) at foot contact with slight progression toward extension by ball release (41 ± 16 degrees). This is a more flexed pattern than that demonstrated by the adults in Fleisig et al. (Fleisig et al., 2006) The inability to achieve greater knee extension at ball release may be related to maturation, level of experience, and lower extremity strength. It may also be a result of pitching from the flat ground. A preliminary comparison of mound versus no mound in adolescent pitchers from the same laboratory showed increased knee extension throughout the pitch cycle in the mound condition. There may also just be inherent differences in knee kinematics between pitchers as published by Matsuo (Matsuo et al., 2001). Matsuo found two distinct knee kinematics that resulted in the highest pitching velocities: (1) progressive knee extension and (2) progressive knee flexion from foot contact through ball release.

\ Insert Table 3 \

Peak hip flexion/extension and adduction velocities and knee flexion and extension velocities were much lower than those found in the upper extremity (Nissen et al., 2007). Peak hip flexion velocity found at about 19% of the pitch cycle followed by peak hip adduction velocity at 36% of the pitch cycle may help to explain the sequence of motion that is needed to transfer energy from the lower extremity to the trunk and ultimately pitching arm and ball (Table 1). Peak knee extension velocity is much lower in amplitude and occurs just before ball release and therefore has less of a role in transferring energy. The lead knee extension velocity at ball release (176 ± 143°/s) in this study was between the velocities reported by Matsuo et al. for their high pitch velocity group (243 ± 149°/s) and their low pitch velocity group (124 ± 141°/s) (Matsuo et al., 2001). However, it should be noted that the Matsuo study was examining collegiate and professional pitchers and not adolescent pitchers.

Knee function can be further described by defining the thigh and shank angles with respect to the laboratory vertical. Not only do these parameters correlate well with the visual assessment of pitching, they allow a better understanding of the contributions to knee flexion. For example, if the shank is nearly vertical, the thigh segment will be the primary contributor to knee flexion. This will have implications on determining strength training needs on a pitcher who has too much knee flexion. The shank was fairly vertical (21 ± 9°) and the thigh much more horizontal (57 ± 11°) at foot contact. There was a minimal progression throughout the pitching cycle of both the thigh and shank to a more vertical position. As a result the change in the degree of knee flexion was also minimal throughout the pitching cycle. This is also reflected in the vertical drop measure which indicates the % drop of the hip joint center in relation to the leg length for the lead leg. As the lead lower extremity knee is always in flexion, this value shows a vertical drop throughout the pitch cycle. As the knee extends through the pitch cycle, there is a reduction in vertical drop. Further study of older pitchers will determine how these parameters differ with increasing experience and strength.

The lead leg ankle remains plantar flexed throughout the pitch cycle with approximately 19 ± 8 degrees range of motion. This is in part due to the orientation of the shank segment in relation to the vertical which shows the distal end of the shank forward of the proximal end throughout the pitch cycle. The heel height of the shoe itself, which is always higher than the toe height (as measured for each pitcher as part of the protocol) contributes to the measured ankle plantar flexion. The data indicates that the lead ankle sagittal plane position is not close to a passive range of motion limitation. Comparative data for similar or older more experienced pitchers is not yet available in the literature. Preliminary data from an internal comparison between mound and no mound pitching collected at the same institution indicates that the ankle kinematics is the primary area of difference when pitching from a mound versus the flat ground. Therefore, it is expected that the ankle plantar flexion in this study will be less than that when pitching from a mound.

The foot position at foot contact during the pitching cycle has been described in the literature as deviation in lead foot position from the midline position (Davis et al., 2009, Dun et al., 2008[AUQ8], Fleisig et al., 1999, 2006). A midline position is considered optimal (Fortenbaugh et al., 2009) though authors have not found an association between foot position and arm loads as defined by peak elbow and glenohumeral moments (Davis et al., 2009). The adolescents in this study on average had a nearly midline foot position at foot contact, placing their lead leg foot only a few centimeters off a line directed at home plate (–2.5 ± 14 cm) toward first base side (open position). There were several pitchers who had large deviations from midline, stepping either in a crossed over open or a closed position (range of foot position distances = –32 to +37 cm). This is most likely a result of a lack of stability and core strength. The mild internal foot progression angle at foot contact (14 ± 17 degrees) demonstrated in this group of adolescent pitchers was slightly less than reported for the adolescents in Dun et al. (22 ± 15 degrees) and collegiate pitchers in Fleisig et al. (19 ± 11°) (Dun et al., 2008[AUQ9], Fleisig et al., 2006). Differences in the kinematic model may in part explain these differences.

Stride length as a percentage of height or stride height ratio is an indicator of the ability of the pitcher to take an appropriate stride of the lead leg relative to height. The mean stride height ratio was 69 ± 6% for the adolescents in this study which was very similar to the adolescents in Dun et al. (70 ± 5%) (Dun et al., 2008[AUQ10]), and the collegiate pitchers in Fleisig et al. (70 ± 4%) (Fleisig et al., 2006). However, in his 1999 study, Fleisig et al. noted a greater stride height ratio (85 ± 8%) in his study of youth pitchers. They measured stride length in the 1999 study as the distance from the lead foot to the pitching rubber while the more recent studies have used the distance between calculated centers of the lead and trailing ankle and this change in technique most likely accounts for differences. The study by Robb et al. (2010), suggests that stride length is likely a result of the passive coronal plane range of motion capability of the leading leg. It is interesting to note the similar values across different ages of pitchers in the stride height ratio.

There are several limitations in this study. First, this study includes individuals in the per-pubertal age range and not older and more skilled pitchers. However, a detailed documentation of the lower extremity biomechanics in adolescent pitching will contribute to the understanding of pitching mechanics. Applying this detailed methodology to high school and college pitchers will help complete our understanding of the development of pitching technique. Second, the pitchers in this study did not throw from a mound. Pitching from the mound is universal and is the optimal research methodology. We are currently evaluating the differences in lower extremity kinematics between mound and no mound pitching for adolescent pitchers to determine if there is any biomechanical basis for pitching from the flat ground when recuperating from injury. Preliminary results show that there were no kinematic differences in the hip and knee between the mound and no mound which is consistent with previous findings (Badura et al., 2003; Fleisig et al., 1996). There was, however, increased ankle plantar flexion at lead foot contact which persisted throughout the pitch cycle in the mound condition. This was consistent with the slope of the mound and the plantigrade position of the lead foot. Timing of the pitching motion was also significantly altered due to the delay in lead foot contact. Ultimately, comparisons with older pitchers should all be made from a mound consistent with how pitchers pitch. However, we are confident that the knee and hip data in this study is reflective of lower extremity pitching technique mound or no mound. Finally, passive range of motion of the hip joint was not taken for these pitchers. Inclusion of passive range of motion will help determine if hip motion during pitching is close to challenging maximum passive range of motion.

In conclusion this paper provides a comprehensive three-dimensional description of the range of motion of the hip, knee, ankle and foot for both the leading and trailing limb during the pitching cycle for adolescent pitchers. Replication of this extensive analysis is recommended for high school, college and professional pitchers to better understand the progression of lower extremity pitching technique with increased experience and strength. This will help contribute to our understanding of the possibility of biomechanically based etiology of injury in the pitchers in terms of the impact of the lower extremity.

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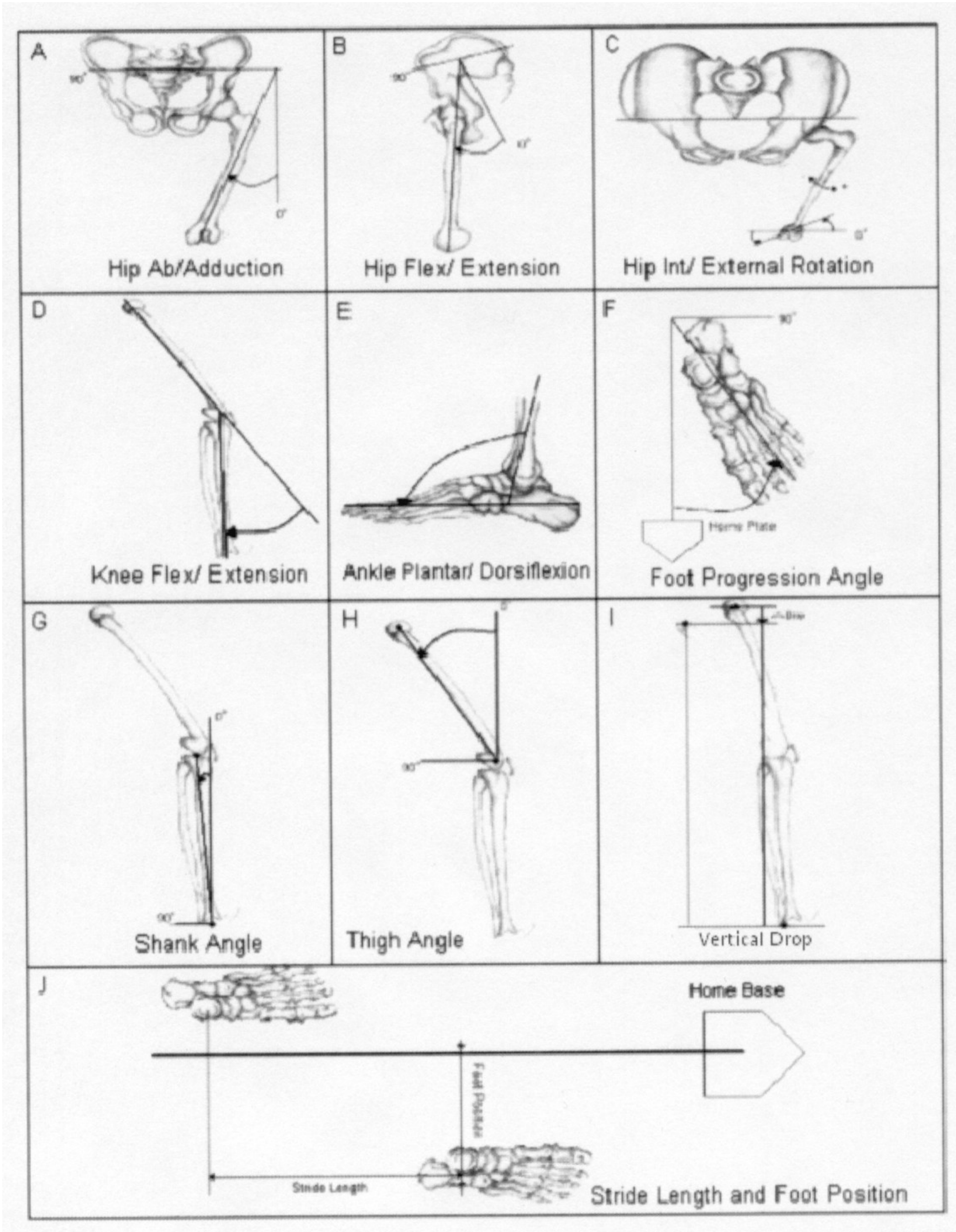

Figure 1 — Joint and segment definitions for the kinematic parameters used in this study. A—Hip Abduction/Adduction, B—Hip Flexion/Extension, C—Hip Internal/External Rotation, D—Knee Flexion/Extension, E—Ankle Plantar/Dorsiflexion, F—Foot Progression, G—Shank Angle, H—Thigh Angle, I—Vertical Drop, J—Stride Length and Foot Position.

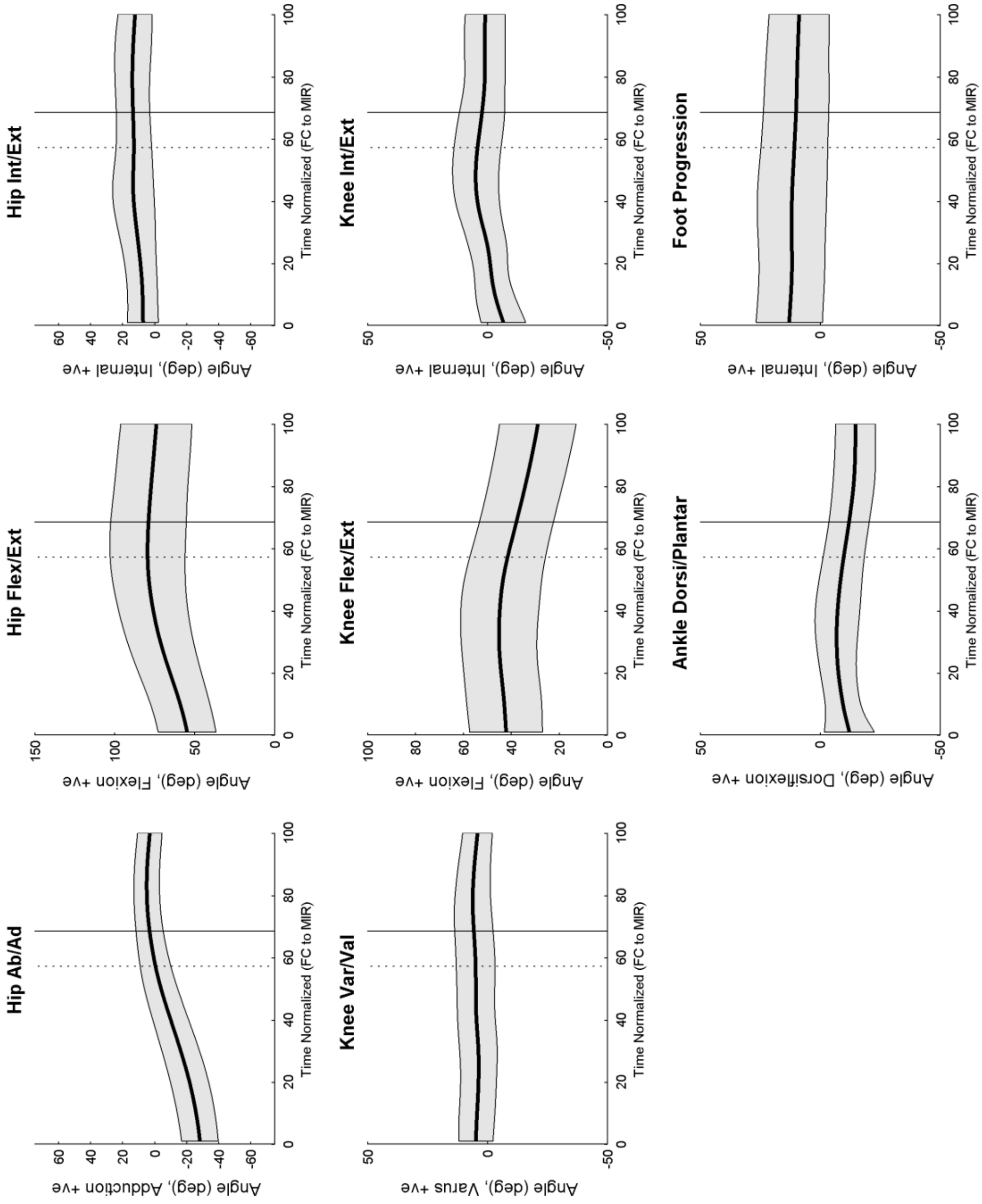

Figure 2 — Joint Kinematics: The mean (± 1 *SD*) lead leg hip, knee, ankle and foot progression kinematics in the coronal (first column), sagittal (second column) and transverse (third column) planes. The dotted vertical line indicates the point in the pitch cycle of maximum external glenohumeral rotation. The solid vertical line indicates the point in the pitch cycle of ball release.

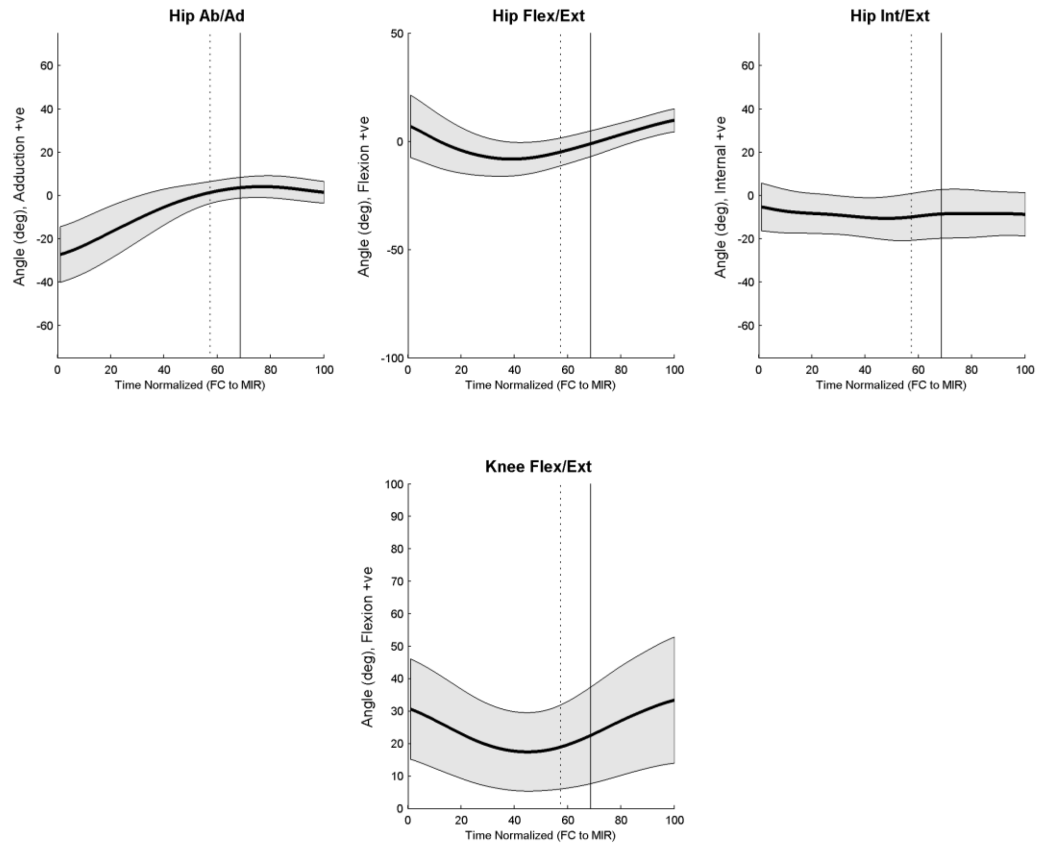

Figure 3 — Joint Kinematics: The mean (± 1 *SD*) trailing leg hip, knee, and ankle kinematics in the coronal (first column), sagittal (second column) and transverse (third column) planes. The dotted vertical line indicates the point in the pitch cycle of maximum external glenohumeral rotation. The solid vertical line indicates the point in the pitch cycle of ball release.

Table 1 Description of the mean (± 1 *SD*) lead leg and trailing leg kinematics for the hip, knee, ankle and foot angle at specific points in the pitching cycle

	Hip Coronal Plane Adduction (+ve) Abduction (–ve)		**Hip Sagittal Plane** Flexion (+ve) Extension (–ve)		**Hip Transverse Plane** Internal Rotation (+ve) External Rotation (–ve)	
	Lead Leg	Trailing Leg	Lead Leg	Trailing Leg	Lead Leg	Trailing Leg
Angles						
Angle at FC (°)	–32 ± 10	–31 ± 12	64 ± 17	8 ± 17	7 ± 11	–6 ± 13
Angle at MER (°)	3 ± 10	4 ± 6	92 ± 14	–2 ± 7	14 ± 13	–10 ± 12
Angle at BR (°)	6 ± 9	5 ± 6	90 ± 14	3 ± 7	15 ± 13	–9 ± 13
Angle at MIR (°)	4 ± 9	2 ± 6	86 ± 15	12 ± 9	13 ± 13	–10 ± 12
ROM (°)	40 ± 10	37 ± 11	30 ± 13	30 ± 11	16 ± 7	17 ± 7
Joint Velocities of Lead Leg			**°/s**	**%PC**		
Max Hip Adduction Velocity			434 ± 83	36 ± 15		
Max Hip Extension Velocity			181 ± 87	80 ± 15		
Max Hip Flexion Velocity			456 ± 156	19 ± 12		
Hip Adduction Velocity at BR			37 ± 109	78 ± 5		
Hip Extension Velocity at BR			94 ± 110	78 ± 5		
			Knee Sagittal Plane Flexion (+ve) Extension (–ve)		**Matsuo et al. Classification of Lead Knee Sagittal Movement**	
			Lead Leg	Trailing Leg	Type	No. of pitchers
Angles					A	13
Angle at FC (°)			49 ± 12	35 ± 22	B	3
Angle at MER (°)			46 ± 15	24 ± 22	C	10
Angle at BR (°)			41 ± 16	30 ± 23	D	3
Angle at MIR (°)			34 ± 18	38 ± 27	E*	3
ROM (°)			22 ± 12	31 ± 11		
Joint Velocities			**°/s**	**%PC**		
Max Knee Extension Velocity			276 ± 134	68 ± 28		
Knee Extension Velocity at BR			176 ± 143	78 ± 5		
			Ankle Sagittal Plane Dorsiflexion (+ve) Plantar flexion (–ve)		**Foot Angle** Internal Rotation (+ve) External Rotation (–ve)	
			Lead Leg		Lead Leg	
Angles						
Angle at FC (°)			–13 ± 12		14 ± 17	
Angle at MER (°)			–13 ± 10		11 ± 17	
Angle at BR (°)			–15 ± 10		10 ± 17	
Angle at MIR (°)			–16 ± 9		9 ± 16	
ROM (°)			18 ± 8			
Foot angle change from FC to MIR			5 ± 6			
Foot position (cm)			–2.4 ± 14			

Note. FC, foot contact; MER, maximal external rotation of the shoulder; BR, ball release; MIR, maximal internal rotation of the shoulder; ROM, Range of motion; PC, pitching cycle.

*Type E pattern with relative knee extension throughout pitching cycle added to original types A–D.

Table 2 Description of the mean (± 1 *SD*) thigh and shank segment positions at specific points in the pitching cycle

Angles	Thigh Angle (0° Vertical, 90° Horizontal)	Shank Angle (0° Vertical, 90° Horizontal)	Vertical Drop (% of leg length)
Angle at FC (°)	57 ± 11	21 ± 9	39 ± 7%
Angle at MER (°)	55 ± 11	11 ± 8	35 ± 7%
Angle at BR (°)	52 ± 12	13 ± 8	34 ± 8%
Angle at MIR (°)	46 ± 12	13 ± 8	30 ± 8%

Note. FC, foot contact; MER, maximal external rotation of the shoulder; BR, ball release; MIR, maximal internal rotation of the shoulder; ROM, range of motion; PC, pitching cycle.

Table 3 Comparison of kinematic parameters between the current study and the literature[AUQ11] [AUQ12]

	Milewski et al. (2010) Adolescents	Fleisig et al. (1999) Youth	Dun et al. (2008) Adolescents	Fleisig et al. (2006) Collegiate
Stride length (% height)	69 ± 6	85 ± 8	70 ± 5	70 ± 4
Knee flexion at FC (°)	49 ± 12	43 ± 12	49 ± 8	38 ± 9
Knee flexion at BR (°)	41 ± 16	36 ± 11	31 ± 9	29 ± 12
Lead foot position at FC (cm)	–2.5 ± 14	na	5.7 ± 12	19 ± 14
Lead foot angle at FC (°)	14 ± 17	na	22 ± 15	19 ± 11

Note. FC, foot contact; BR, ball release.

Author Queries

[AUQ1] The citation "Dun et al., 2008" matches multiple references. Please add letters (e.g. "Smith 2000a"), or additional authors to the citation, to uniquely match references and citations.

[AUQ2] The citation "Dun et al., 2008" matches multiple references. Please add letters (e.g. "Smith 2000a"), or additional authors to the citation, to uniquely match references and citations.

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[AUQ11] The in-text citation "Milewski et al. (2010)" is not in the reference list. Please correct the citation, add the reference to the list, or delete the citation.

[AUQ12] The citation "Dun et al. (2008)" matches multiple references. Please add letters (e.g. "Smith 2000a"), or additional authors to the citation, to uniquely match references and citations.