KINEMATIC COMPARISON OF MARKER SET TECHNIQUES USED IN BIOMECHANICAL ANALYSIS OF THE PITCHING MOTION

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Thesis

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ABSTRACT

The purpose of this investigation was to determine if two different reflective marker methods yielded significantly different results when calculating joint centers and kinematic data for collegiate baseball pitchers. Five healthy collegiate baseball pitchers participated, each throwing ten fastballs. Of the fifty trials, 44 pitches were statistically analyzed. The subjects' body motions were recorded using an 8-camera, high speed (240-Hz), automatic digitizing system (Motion Analysis Corporation, Santa Rosa, California) following application of the combination 46-marker set on each subject. Kinematic parameters were calculated at foot contact, ball release, and at three kinematic maximums. The average kinematic variables were determined for each subject and then were combined within each parameter for statistical analysis. Comparison of the two methods was performed using a paired t-test ($\alpha = 0.05$). Statistically, this test determined that shoulder external rotation at foot contact ($t < t_{critical}$, $0.7330 < 2.023$) and maximum shoulder horizontal adduction ($t < t_{critical}$, $0.8595 < 2.025$) were the only kinematic parameters that had no significantly different results between the two methods. However, when looking at the individual subject data, there were differences of at least ten degrees for several of the subjects within each parameter. This would not be acceptable in the realm of clinical significance for baseball pitching mechanics. In this case study, since over half of the subjects for both of the statistically non-significant parameters had

average differences of ten degrees or more, the statistical non-significance loses its credibility in the clinical environment. This indicates that the two methods produce significantly different results and should not be used for data comparison.

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CHAPTER I

INTRODUCTION

The pitching motion in baseball is a complex sequence of events. Not only does it involve the coordination of the throwing arm to release the ball for optimal velocity and control, but it also requires necessary motions from the legs, up through the trunk, and out to the throwing extremity. Most scientific studies involving the biomechanics of the pitching motion are generally concerned with the shoulder and elbow joints of the throwing limb. A few other selected studies are now beginning to incorporate the effects of the trunk, hips, and legs on a person's ability to throw a baseball or softball. By studying and analyzing the motions involved in pitching, scientists and engineers are hoping to determine the optimal mechanics for throwing to minimize the amount of stress one places on their arm while throwing at such high velocities.

An integral part to analyzing the kinematic and kinetic motions of an athletic sequence, such as the pitching motion, is the placement of the reflective markers that are detected by the camera system for the study. A number of different marker systems have been used in previous studies. The optimal number of markers needed in order to obtain the necessary data for further calculations has yet to be determined. In order to calculate all of the important kinematic and kinetic parameters, a certain number of markers are required at specific body locations, such as bony landmarks. It would be ideal to determine a minimal number of locations to use for the study, but it is still imperative to mark the significant landmarks. The more markers used will bring about an increased risk for one of the markers to fall off throughout the study due to the rigorous throwing motion or sweat that has accumulated while pitching.

One of the main reasons for this increased interest in analyzing the biomechanics of the pitching motion is to prevent arm injuries that are plaguing athletes today. Prior statistical research looked at the number of pitching disabilities occurring at the Major League level (Conte, Requa, & Garrick, 2001). Statistical data from the 1989 season showed that 26 Major League Baseball teams experienced 118 pitching disabilities for a total loss of 8319 days. Ten years later in 1999, the 30 Major League Baseball teams had 182 pitching disabilities accounting for 13,129 disabled days. Over the course of these ten years, there was a 15% increase in the number of teams and players in Major League Baseball, but there was a 54% increase in the number of pitchers placed on the disabled list accounting for a 58% increase in the duration of time they missed during the season. This is a major cause for concern. One of the primary reasons for the necessity of biomechanical studies evaluating the biomechanics of pitching is to reduce this increasing number of injuries to baseball pitchers.

The most commonly known pitching injuries that occur at the Major League and collegiate level revolve around the shoulder complex and the ulnar collateral ligament of the elbow. The shoulder joint is a ball-and-socket joint where the humeral head fits loosely into the glenoid cavity. Due to its tremendous range of motion, the farther a pitcher is able to bring his arm back into abduction and externally rotate his shoulder, the faster the ball will go when released (Baker & Ayers, 2003). The lack of bony restriction in the shoulder joint forces a reliance on relatively weak soft-tissue structures to maintain shoulder stability. These soft-tissue stabilizers feel the greatest stress during the throwing motion and are the most frequently injured structures when this stress is applied repeatedly.

There are two groups of soft-tissue stabilizers associated with the shoulder complex. The static stabilizers refer to the ligaments of the shoulder capsule and the labrum which surrounds the socket of the glenoid cavity. The labrum is an important part of the thrower's shoulder anatomy because it serves as an attachment site for several capsular ligaments at the glenoid and it also deepens the socket portion of the joint to provide extra stability. The dynamic stabilizers include the rotator cuff muscles (supraspinatus, infraspinatus, teres minor, and subscapularis) which surround the shoulder and contract at different times during the various stages of throwing. The static and dynamic stabilizers work together to adhere the humeral head in the glenoid cavity during the act of throwing. If the soft tissue stabilizers become too loose or too tight, the delicate balance of humeral head stability is thrown off, resulting in abnormal movement of the humeral head during throwing often resulting in increased stress and pain. This abnormal movement of the humeral head puts increased stress on the labrum and can lead to a tearing away of the labrum from the glenoid. This is referred to as a SLAP (Superior Labrum Anterior to Posterior) lesion, which is one of the major causes of pain in the thrower's shoulder (Baker et al. 2003).

The elbow joint acts as a hinge joint that receives its power from the biceps and triceps muscles. During a throwing motion, the throwing elbow is part of a chain. The hand is like the end of the whip, and as the trunk rotates, the hand is forcefully left behind. The shoulder and elbow act as the links between the trunk and hand. As the shoulder rotates back and then suddenly forward (external rotation and then internal rotation), the momentum generated by the trunk rotation is multiplied. The momentum change when the shoulder changes from cocking to acceleration puts the elbow under tremendous stress. The ligament on the medial side of the elbow, the ulnar collateral ligament (UCL), is subjected to forces large enough to tear it on almost every hard throw. The reason why it doesn't tear every time is because the nearby muscles help to protect it. If an athlete throws too hard and too often, or if his or her mechanics are poor, the stress on the ligament can be too great, thus causing a tear. This is a serious injury, and often requires surgery to fix, commonly known as the "Tommy John" surgery today (MEDCO Sports Medicine, 2004).

According to the research provided by Conte et al. (2001), the majority of baseball injuries are associated with the shoulder and elbow joints. From 1995 to 1999, the number of days spent on the disabled list for Major League baseball players was broken down per anatomic region. Out of more the 69,000 days spent on the disabled list, 27.8% of the disabled list days were a result of shoulder injury. Another 22.0% of the total disabled list days dealt with elbow injuries. Also a note of importance, was the consistent increase in elbow disabled list days over the course of this five-year period. This has also been noted by Olsen, Fleisig, Dun, Loftice, & Andrews (2006) as they reported a six-fold increase in the number of elbow surgeries performed on high-school pitchers from 2000-2004 compared to 1994-1999. Due to the repetitive nature of pitching, pitchers are at great risk for sustaining an injury to the shoulder or elbow region (MEDCO Sports Medicine, 2004).

Injury prevention can be started with youth baseball players by limiting the number of pitches thrown over the course of a particular season. Starting in 2007, youth pitchers affiliated with Little League Baseball will be subjected to a pitch count per game which in turn will determine the amount of rest required before their next pitching performance (Little League Baseball 2007, Patrick 2006). Another option to help prevent shoulder or elbow throwing injuries is to undergo a biomechanical analysis which uses reflective markers placed on the athlete's body to help detect various arm and body angles as well as forces and torques applied to the joints associated with the throwing motion. If the pitching motion is abnormal or places an unreasonable load on a specific part of the body, suggestions may be made to help promote a more fluid motion thus hoping to prevent future injury.

Two of the more established marker systems used to analyze the biomechanics of the pitching motion have been formulated by Glenn S. Fleisig of the American Sports Medicine Institute in Birmingham, Alabama, and Motion Reality, Inc. located in Atlanta, Georgia. While both marker systems have shown the ability to quantify various kinematic and kinetic parameters, it would be beneficial for future studies involving the biomechanics of the pitching motion to only use one marker system. This would make data comparison easier due to a standardized methodology for data acquisition for testing at any location.

A study has been proposed using collegiate pitchers to compare these two marker systems and their respective kinematic data. The null hypothesis for this study is as follows:

H_0: There is no significant statistical difference between the joint centers and the kinematic parameters determined using the marker systems designed by Fleisig and Motion Reality, Inc.

The alternate hypothesis was:

H_1: There is a significant statistical difference between the joint centers and the kinematic parameters determined using the marker systems designed by Fleisig and Motion Reality, Inc.

To determine the joint center positions and kinematic parameters, anthropometric and motion analysis data were collected from the subjects involved with the study. The motion analysis data, combined with the anthropometric data of various body segments allowed for the derivation of the various joint centers which in turn helped to provide the various coordinate systems needed to calculate the kinematic parameters associated with the pitching motion.

With the alarming increase in pitching injuries noted today, there has been an increased interest in ways to help prevent these injuries from occurring. The results of this study will be valuable in determining a consistent method for studying the biomechanics of the pitching motion.

CHAPTER II

LITERATURE REVIEW

The pitching motion is very complex and three-dimensional. This has led to many different methodologies being used to analyze the biomechanics of the pitching motion. Different temporal, kinematic, and kinetic parameters are selected based upon their necessity for each individual study. Also a variety of methods are being used to collect the motion data including varying numbers and locations for the reflective markers commonly associated with motion analysis research.

2.1 Background of Pitching Biomechanics

Upon initial review, it appears as though the majority of the muscle and joint activity involved in pitching a baseball occurs in the upper body, specifically the shoulder and elbow. This impression is acquired due to that fact that most professional baseball pitching injuries are related to the shoulder or elbow. The most common musculotendinous injuries sustained by baseball pitchers occur within the rotator cuff region (Mullaney, McHugh, Donofrio, & Nicholas, 2005). Since pitching is such a rigorous and repetitive motion, many of these injuries can be attributed to overuse or improper mechanics.

Fleisig et al. (2006) and Conte et al. (2001) noted the number of pitching disabilities observed over the course of several Major League Baseball seasons.

Statistical data from the 1989 season showed that 26 Major League Baseball teams experienced 118 pitching disabilities for a total loss of 8319 days. Ten years later in 1999, the 30 Major League Baseball teams had 182 pitching disabilities accounting for 13,129 disabled days. Over the course of these ten years, there was a 15% increase in the number of teams and players in Major League Baseball, but there was a 54% increase in the number of pitchers placed on the disabled list accounting for a 58% increase in the duration of time they missed during the season. This is a major cause for concern. One of the primary reasons for the necessity of biomechanical studies evaluating the biomechanics of pitching is to prevent this increasing number of injuries to baseball pitchers.

The pitching motion can be broken down into several key temporal parameters based on distinct motions involved in every pitch. Different studies use different temporal parameters based on the needs for the study. Werner, Gill, Murray, Cook, & Hawkins, (2001) broke down the pitching motion into three phases: stride foot contact to the instant of maximum shoulder external rotation (cocking phase), maximum external rotation to the instant of ball release (acceleration phase), and from ball release until 500 milliseconds after the ball has been released (follow-through phase). Another study performed by Sabick, Kim, Torry, Keirns, & Hawkins (2005) used a slightly altered set of temporal parameters. Their research involved four phases but used some of the visual landmarks seen in the Werner et al. (2001) study. Sabick and her colleagues defined phases as the ball leaving the mitt until stride foot contact, stride foot contact until maximum shoulder external rotation, maximum shoulder external rotation to ball release, and ball release to maximum internal rotation.

It may appear that studying the ground-reaction forces involved in baseball pitching might require different temporal parameters than studies just looking at upper body motion. However, a ground-reaction force study by MacWilliams, Choi, Perezous, Chao, & McFarland (1998) incorporated many of the same temporal variables. Their temporal variables were maximal anterior-posterior shear at push-off, landing leg foot contact, maximal shoulder external rotation, ball release, and follow-through. Although different calculations are being made and different biomechanics are being analyzed, similar temporal parameters are used when studying the baseball pitching motion.

The most in-depth set of temporal parameters can be seen in the Fleisig et al. (2006) study. This specific study divided the analysis into six phases and involved wind-up mechanics. The wind-up phase starts from the initial position until the lead knee reaches its maximum elevation. Stride phase lasts from maximum knee height until lead foot contact is established. Arm cocking occurs from the foot contact until maximum shoulder external rotation. Arm acceleration is from maximum shoulder external rotation until ball release and arm deceleration spans from ball release to maximum shoulder internal rotation. Finally, the follow-through phase was determined to be the time after maximum shoulder internal rotation until the pitching motion stopped and the pitcher was done moving. A visual reference for the temporal parameters used by Fleisig et al. (2006) can be seen in Figure 2.1. The temporal phases used depend on the kinematic variables calculated, thus making the consistency and accuracy of these variables even more important. These temporal parameters then will allow for increased sets of kinematic and kinetic data to be analyzed throughout the course of the pitching motion.

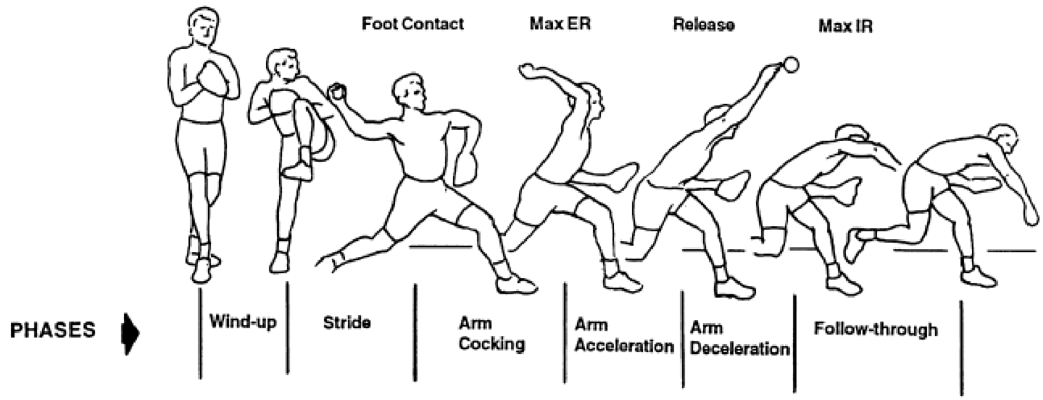

Figure 2.1 Temporal phases of pitching mechanics (Fleisig et al. 1996, 1999, 2006)

It is very important to define what kinematic and kinetic parameters are being looked at throughout the course of the study, as well as how these parameters are obtained through calculations. Fleisig and his co-workers (2006) looked at the kinematic parameters of elbow flexion, wrist extension, shoulder external rotation, shoulder horizontal adduction, lateral trunk tilt, knee flexion, forward trunk tilt, pelvis angular velocity, upper trunk angular velocity, stride length, foot angle, and foot position. Figure 2.2 shows how each parameter was evaluated based on the acquired data. In the same study by Fleisig et al. (2006), kinetic parameters selected for evaluation included the forces applied by the trunk to the upper arm at the shoulder, torques applied by the trunk to the upper arm about the shoulder, forces applied by the upper arm to the forearm at the elbow, and torques applied by the upper arm to the forearm at the elbow. The definitions of these kinetic parameters are shown in Figure 2.3.

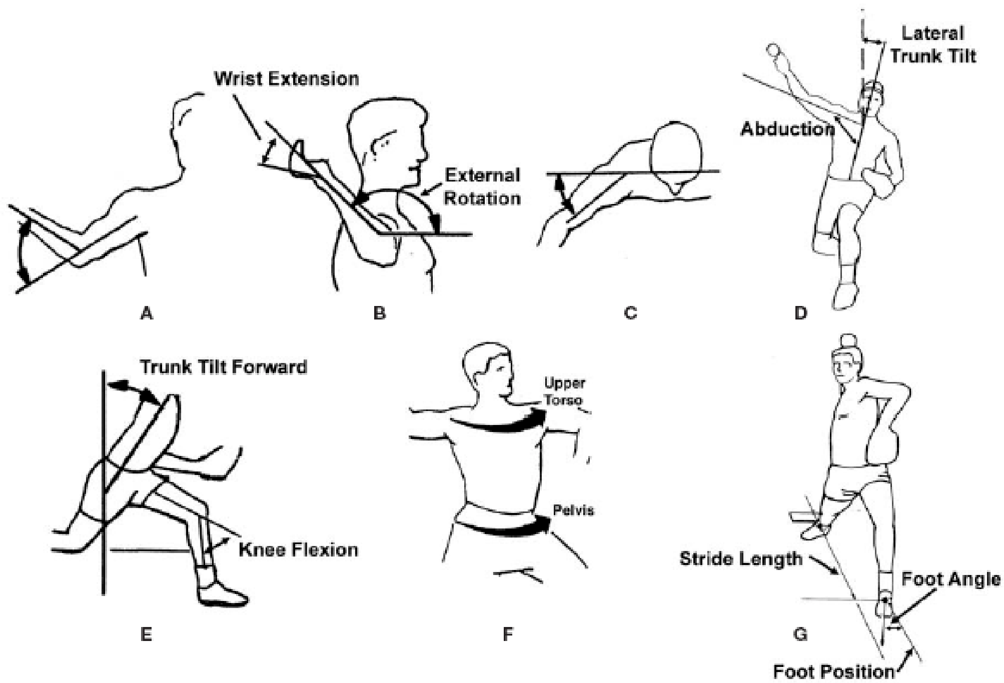

Figure 2.2 Definition of kinematic parameters (Fleisig et al. 2006)

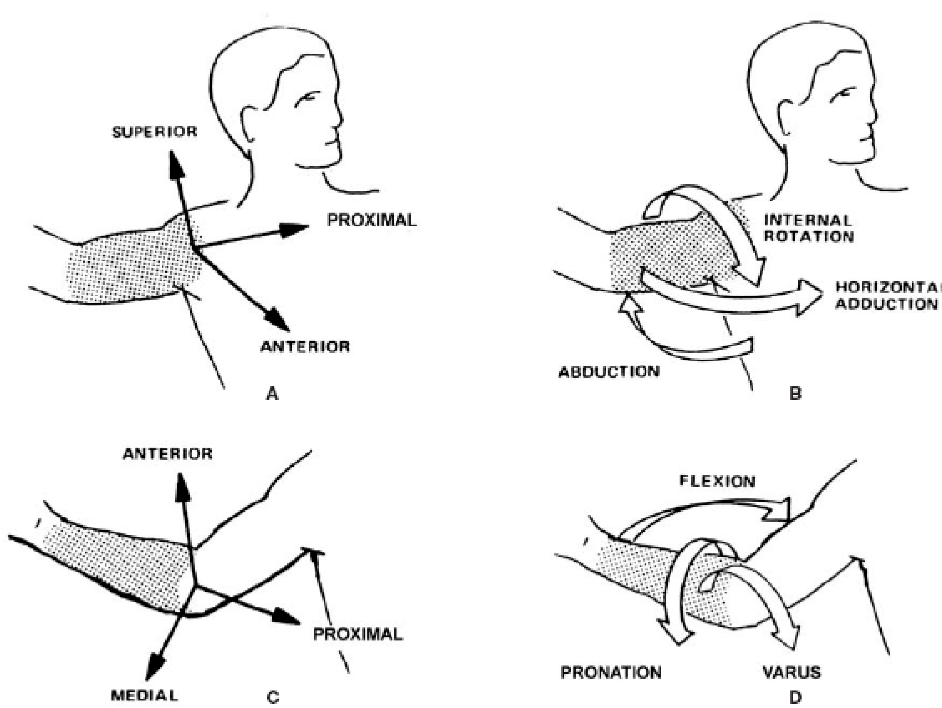

Figure 2.3 Definition of kinetic parameters (Fleisig et al. 2006)

Unless the specific study is looking at the kinematic and kinetic effects of different pitches, the subjects being analyzed will throw fastballs at the desired target. This makes for more uniform sampling as well as easier data comparison among subjects because every pitcher throws a fastball in a similar manner to achieve a high velocity. It is rare to find testing or data collection performed during game situations. If this is the method chosen for data acquisition however, anatomical landmarks must be manually digitized and camera angles must be accommodating to the baseball field's facilities and grounds. Most studies are performed in a lab with multiple-high speed cameras at various angles to capture all of the reflective markers located on the body to calculate various kinematic and kinetic parameters.

2.2 Previous Studies Findings

As mentioned earlier, many different studies have obtained results for different kinematic and kinetic parameters. In the study by MacWilliams et al. (1998), ground-reaction forces were investigated rather than the common upper body parameters of the shoulder and elbow. Their belief was that poor pitching mechanics may originate in the lower extremities because the whole body is involved when pitching a baseball. The two points of measurement were the push-off from the back leg, and the landing leg at stride foot contact. Pitchers were found to generate a shear force of approximately 35% of their body weight in the direction of the pitch with their push-off leg. Later on in the pitching motion, resisting forces of approximately 72% of the subject's body weight were calculated for the landing leg. When comparing this data to different wrist velocities while pitching a baseball, there was a strong correlation of wrist velocity to increased leg driving forces. Therefore, this study by MacWilliams and his co-workers validated the fact that the lower extremity is a very important contributor to the pitching motion when throwing off a mound.

A different study performed by Sabick et al. (2005) looked at the effects of repetitive throwing on the shoulder joint for developing, young athletes. In their research they primarily looked at the net forces and torques acting on the humerus during the course of a pitching motion. After defining the local coordinate systems at the shoulder and elbow (Figure 2.4), the selected 12-year old youth baseball pitchers were tested while throwing several fastballs in a simulated game to the desired strike zone. The results

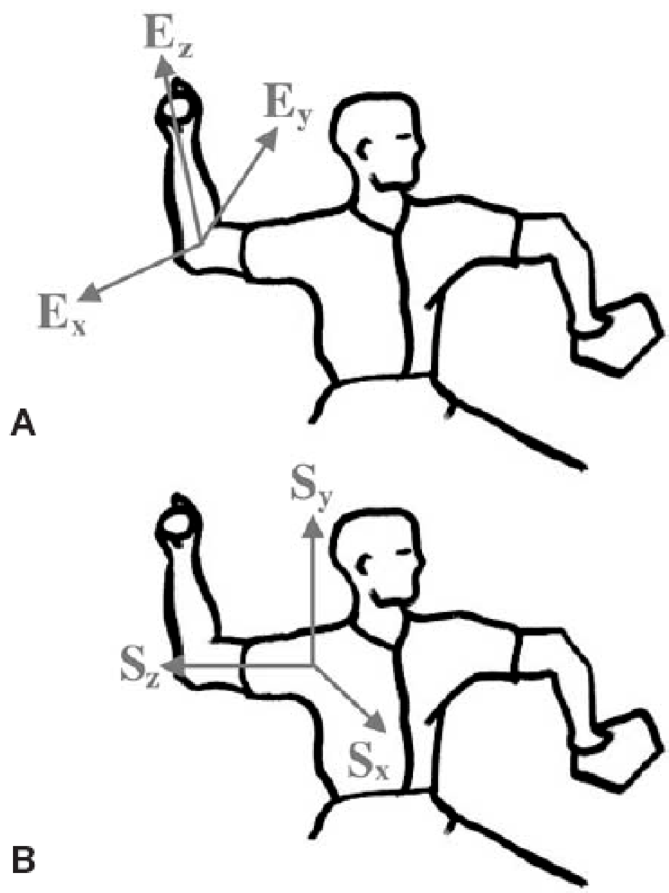

Figure 2.4 Definition of local elbow and shoulder coordinate systems (Sabick et al. 2005)

indicated that external rotation torque about the long axis of the humerus reached its peak value of 17.7 Nm, or 2.7% body weight times height and occurred just prior to maximum external shoulder rotation. Shoulder distraction force was also calculated to be 214.7 N, or 49.8% of the body weight of the subject, occurring just after ball release. By providing such kinetic data for youth baseball pitchers, injury mechanisms may begin to be derived from this study based on repetitive throwing.

Werner et al. (2001) performed an experiment looking at the relationship between pitching mechanics and shoulder distraction. Due to the extreme forces and torques associated with the pitching motion, a tremendous amount of stress is placed upon the soft tissues in the throwing shoulder. Following multiple kinematic and kinetic calculations, a significant distraction force at the shoulder was calculated to have an average peak value of 947 N. When compared to the temporal and kinematic parameters assigned, shoulder distraction was correlated to the elbow angle at stride foot contact and ball release, the position of the shoulder at maximum external rotation, and the peak external rotation and abduction torques. The significance of this study was that shoulder joint distraction indicated potential for injuries associated with the rotator cuff and glenoid labrum, two common sites for injuries in baseball pitchers. Knowledge of the joint ranges of motion, angular velocities, and joint reaction forces calculated in this study can be used to supply preventative and rehabilitative protocols for baseball pitchers in the future.

The relationship between multiple biomechanical factors to pitching velocity was examined by Stodden, Fleisig, McLean, & Andrews (2005). Ball velocity was compared to twelve kinematic, seven kinetic, and eleven temporal parameters to see which specific parameters could be correlated with an increased pitching velocity. Three kinematic parameters (decrease in shoulder horizontal adduction at foot contact, decreased shoulder abduction during acceleration, and increased trunk tilt forward at ball release), three kinetic parameters (elbow flexion torque, shoulder proximal force, and elbow proximal force), and two temporal parameters (increased time to maximum shoulder horizontal adduction and decreased time to maximum shoulder internal rotation) were significantly related to an increase in pitched ball velocity. This information showed that variations in an individual's pitching mechanics attribute to ball velocity, and that consistent mechanics should be used to produce more consistent high velocity fastballs.

Another type of study compared the mechanics of pitching to the mechanics of passing a football (Fleisig, Escamilla, Andrews, Matsuo, Satterwhite, & Barrentine, 1996b). It has been proposed for baseball pitchers to throw footballs as weighted implements to help strengthen the arm to increase pitching velocity. Once again, many different kinematic, kinetic, and temporal parameters were looked at for comparison of the two throwing motions. Results from the study showed that football passing did not produce greater forces or torques when throwing. Instead, greater forces and torques for the shoulder and elbow were present in the deceleration phase for baseball pitchers which may explain why injuries are so common in baseball. Higher arm speeds were calculated for baseball pitching than football passing, but using the other type of motion to help generate greater arm speed may be detrimental because there are differences in the throwing mechanics for each sport. In addition to this study, the biomechanics of the elbow in throwing athletes was also researched by Fleisig & Escamilla (1996a).

Kinematic differences in the pitching motion were also compared for full-effort and partial-effort pitching (Fleisig, Escamilla, Barrentine, Zheng, Andrews, & Lemak, 1996d). Partial-effort throwing is common for warming up, rehabilitation, and reinforcing proper timing throughout the entire motion. For the study, pitchers were given the instruction to throw at 50%, 75%, and 100% effort, although those effort values can be extremely vague. At 75% effort, the pitchers threw at approximately 90% velocity and experienced 90% arm and trunk speed compared to full-effort. At 50% effort, ball speed was reduced to 85%, as was the arm and trunk speed for the pitcher. The reduced effort levels corresponded with reduced arm rotation during the cocking phase, increased horizontal adduction, and less knee flexion and trunk tilt at ball release.

Fleisig, Escamilla, Barrentine, Zheng, & Andrews, (1996c) continued their research on the biomechanics of the pitching motion by comparing the pitching motions on flat ground and the pitching motions while throwing off a mound. Since most baseball throwing injuries are experienced by pitchers, differences between the two methods of throwing might help explain why pitching injuries occur more frequently. Results showed that throwing from flat ground corresponded to a shorter stride and less external rotation of the shoulder at foot contact. Thus, the slight drop in mound elevation allows for an increased stride length as well as more time for the shoulder to externally rotate. At the time of ball release, the pitcher's trunk was found to be more vertical when throwing off flat ground; however, relative to the throwing surface, the trunk angle was similar for mound and flat-ground throwing. Overall, the kinematics of the pitching motion did not vary significantly when comparing a typical pitching motion off a regulation mound and pitching off of a flat surface.

In order to see the differences in the pitching motion at various levels of competition, Fleisig, Barrentine, Zheng, Escamilla, & Andrews, (1999) completed a comparison study among various age groups. Youth, high school, college, and professional pitchers were analyzed for comparison. Similar to the Fleisig et al. (1996b) study, kinematic, kinetic, and temporal parameters were chosen to be compared between the different age groups. Only one of the eleven kinematic parameters showed significant differences among the groups and none of the six temporal parameters were significantly different. However, all eight kinetic parameters increased significantly with competition level. The increases in joint forces and torques were attributed to the increased strength and muscle mass for the higher level athlete. Therefore, since kinematic and temporal parameters show little variance between young and old pitchers, it is critical to develop proper pitching mechanics at a young age. As the body matures, strength will be developed to provide for the greater forces and torques necessary to throw at the high velocities seen at the professional level.

Another study completed by Fleisig et al. (2006) chose to look at the variation between different types of pitches rather than looking at only the fastball. Other pitches chosen for comparison included the curveball, change-up, and slider. There has been a theory submitted stating that breaking pitches (curveball and slider) are more stressful to the arm than the standard fastball. Kinematic, kinetic, and temporal parameters were looked at with a more focused analysis revolving around the kinetic parameters for each pitch. There was only one significant kinetic difference between the fastball and curveball, elbow proximal force. There was also only one significant kinetic difference between the fastball and slider, shoulder horizontal adduction torque. The changeup had significantly lower values for shoulder and elbow kinetics suggesting that this pitch may have the lowest injury risk potential. Significant kinematic differences for all the pitches may provide different force contributions to specific elbow ligaments, tendons, or other tissues which may be why throwing curveballs compared to fastballs appears to provide more stress to the elbow joint complex.

The kinematics of the pitching motion have also been analyzed for pitchers in a fatigued state (Escamilla et al., 2007). For this study, a pitcher's motion was compared from the first two innings thrown, to their last two innings thrown over the course of a simulated seven to nine-inning game. Contrary to popular belief, there was very little change in the biomechanics over the course of this simulated game. The only significant differences found were a decrease in ball velocity and a more vertical trunk position.

The volume of research directed towards the biomechanics of the pitching motion continues to increase each and every year. All of these studies are important to the scientific baseball community in hopes to minimize the risk for injury while pitching. That is why it is extremely important to determine a uniform method for collecting data revolving around the biomechanics of the pitching motion.

2.3 Marker Placement

In order to collect data for such a high-speed motion, photogrammetric reconstruction is the most common method chosen. This is a process which creates a three-dimensional object from two or more two-dimensional projections of the object being studied. To track the specific locations, at least three non-collinear markers located on the body must be identified by two or more cameras at the same time. The human body, while not a true rigid body, can be broken down into a series of jointed segments approximated to be rigid bodies. Knowing the locations and orientation of each rigid body from the markers captured by the cameras, the six motions (three translations and three rotations) may be determined for two adjacent, jointed segments.

Once the markers are captured on film, the process of digitizing to extract the coordinates from the images follows. One way of digitizing is manual digitization when there are no active or passive markers attached to the subject's body, as in the case of a live competition (Sabick et al. 2005, Werner et al. 2001). This method is much more difficult due to a limited number of cameras as well as digitizing through clothing to approximate joint centers, which can be a rather tedious and inaccurate process.

The use of markers attached to pertinent bony landmarks makes the digitization process much easier. This allows for automatic digitizing or real-time digitizing because the body is being represented by the specific markers. There are two types of markers that may be used for body detection: active and passive. Active markers required an external supply of energy as in the case of Light-Emitting Diodes (LED). These active markers are turned on in a sequential manner that allows the cameras to identify the spatial locations of any marker that is emitting light at any instant of time. The major down-side to using these active markers is that they require wires to be attached which make the pitching motion nearly impossible. Even if the wires were long enough to prevent motion restriction, the wires would still fly around and hit the subject making it extremely uncomfortable and provide an unnatural setting to pitch a baseball.

Passive markers are most commonly used and reflect light in the direction from which it comes. The cameras used to collect data will simultaneously gather information from the passive reflective markers that appear on the video screen as bright dots. At the

American Sports Medicine Institute (ASMI), eight electronically synchronized, 240 Hz, infrared cameras are used to transmit pixel images of the reflective markers attached to the baseball pitcher directly to a video processor (Motion Analysis Corporation, Santa Rosa CA).

The marker system used for the previous studies was critical in determining how kinematic and kinetic values were calculated. Euler angles are not commonly associated with shoulder joint calculations. This is because the range of motion for the shoulder may include a position where two body-fixed axes may become parallel and co-linear, meaning a joint coordinate system must be used. The type of study and joints analyzed generally dictates how a coordinate system is determined from the markers placed on the pitcher's body. The number of markers used, and the placement of these markers on significant anatomical landmarks, are the key factors being looked at for this study.

When looking at ground-reaction forces, as MacWilliams et al. (1998) did, individual reflective markers were placed on bony landmarks at the ends of the midtoes, lateral malleoli, lateral femoral condyles, greater trochanters, tips of the acromions, lateral humeral epicondyles, wrists, and the sacrum. These locations were selected to minimize the bulk of too many markers while allowing for tracking the pitching motion with high-speed cameras. Although the primary concern for this study looked at the ground-reaction forces at push-off and landing, MacWilliams and his co-workers calculated internal-external rotations for the hips and shoulders based on the position of the more distal segment assuming a rigid, hinged connection between these segments.

A more specific look at the shoulder and elbow joints taken by Sabick et al. (2005) opted not to use reflective markers. Instead, from the videotapes of high-speed video cameras, 21 bony landmarks were manually digitized in each camera view. The specific locations for these landmarks were not mentioned. Using direct linear transformation (Abdel-Aziz & Karara, 1971), these digitized landmarks were assigned their three-dimensional coordinates. In order to reference forces and torques applied to the shoulder and elbow joints, local coordinate systems were defined for the shoulder and elbow, respectively (Figure 2.4).

Werner et al. (2001) also decided to use the manual digitizing technique for marking specific anatomical locations. Once again, specific locations for the manually digitized landmarks were not mentioned. Similar to the study provided by Sabick et al. (2005), Werner et al. (2001) used the direct linear transformation method to obtain three-dimensional coordinate data for both the ball and each manually digitized landmark. The reference frames for both the shoulder and elbow joints are exactly the same as the coordinate systems used by Sabick et al. (2005) in Figure 2.4. Based on these two studies it appears when manually digitizing bony landmarks there is some consistency as to how the coordinate data are quantified to obtain the kinematic and kinetic parameter values.

Although no literature has been presented in a scientific journal regarding a marker system applied by Arnel Aguinaldo and the San Diego Center for Human Performance, a manual (Aguinaldo, 2005) has been supplied to show how their marker analysis is completed. Using a software program, UETrak 1.2, upper extremity kinematics and kinetics are calculated based on the body marker set. This full body marker set combines an eight segment upper body marker set (two upper arms, two lower arms, one hand, two shoulder girdles, and one head) with the Helen Hayes marker set for the lower body (Table 2.1, Figure 2.5). When referencing the shoulder joint, the three markers placed on the scapula define the glenohumeral joint center of activity. Markers may also be applied to the radial styloid, ulnar styloid, and the fifth metacarpal joint to calculate wrist kinematics such as wrist flexion and ulnar deviation for the throwing arm.

Kinematic calculations are based upon a joint coordinate system for each joint being looked at. Joint center estimations were defined relative to the reflective markers. The glenohumeral joint was estimated relative to the three markers placed on the shoulder girdle. Wrist joint center was referred to as the midpoint between the radial and ulnar styloid markers. Elbow joint center was referenced to the plane defined by the glenohumeral joint, the elbow lateral epicondyle, and the wrist joint center. The intermediate coordinate system is used to define the elbow joint center because a marker cannot be placed on the medial epicondyle of the elbow due to high motion restrictions involved with pitching. The list of potential kinematic parameters UETrak can calculate includes: shoulder joint motion, elbow flexion, forearm pronation/supination, wrist flexion/extension, head tilt, trunk tilt, pelvis rotation, and segment angular velocities. Specific baseball parameters such as stride length or ball speed may also be incorporated into this model.

Motion Reality, Inc. (MRI) applied a 46-marker system to the pitcher's body for motion analysis (Figure 2.6). While some markers are used to define joint centers more directly, other markers such as those placed on the back and waist help to define the body type of each individual (J. Nason, personal communication, June 20, 2006). From the markers and an assortment of calculations, a virtual image of the pitcher is created. Then, from the virtual image, joint centers can be estimated based on anatomical calculations.

Table 2.1 San Diego Center for Human Performance marker setup (Aguinaldo, 2005)

	Right-Dominant	Left-Dominant	Comments
1	R.Acromion	R.Acromion	
2	R. Clavicle	R. Clavicle	Can be placed anywhere on the clavicle for asymmetry
3	L.Acromion	L.Acromion	
4	L.Head	L.Head	
5	Top.Head	Top.Head	
6	R.Head	R.Head	
7	L.Wrist.Rad	R.Wrist.Rad	
8	L.Epi.Lat	R.Epi.Lat	Lateral epicondyle of the humerus
9	L.Scap.Inf	R.Scap.Inf	Inferior angle of the scapula
10	L.Scap.Med	R.Scap.Med	Root of scapular spine
11	R.Scap.Med	L.Scap.Med	Inferior angle of the scapula
12	R.Scap.Inf	L.Scap.Inf	Root of scapular spine
13	R.Epi.Lat	L.Epi.Lat	Lateral epicondyle of the humerus
14	R.Wrist.Rad	L.Wrist.Rad	
15	R.Wrist.Uln	L.Wrist.Uln	
16	R.Hand *	L.Hand *	5^{th} MCP joint * needed for wrist calculations
17	R.ASIS	R.ASIS	
18	R.PSIS	R.PSIS	
19	V.Sacral	V.Sacral	
20	L.ASIS	L.ASIS	
21	R.Thigh	R.Thigh	Wand marker
22	R.Knee	R.Knee	
23	R.Shank	R.Shank	Wand marker
24	R.Ankle	R.Ankle	
25	R.Heel	R.Heel	
26	R.Toe	R.Toe	Must be parallel with heel marker
27	L.Quad	L.Quad	Can be placed anywhere on anterior thigh for asymmetry
28	L.Thigh	L.Thigh	
29	L.Knee	L.Knee	
30	L.Shank	L.Shank	
31	L.Ankle	L.Ankle	
32	L.Heel	L.Heel	
33	L.Toe	L.Toe	Must be parallel with heel marker
34	R.Knee.Med	R.Knee.Med	Removed after static calibration
35	R.Ankle.Med	R.Ankle.Med	Removed after static calibration
36	L.Knee.Med	L.Knee.Med	Removed after static calibration
37	L.Ankle.Med	L.Ankle.Med	Removed after static calibration

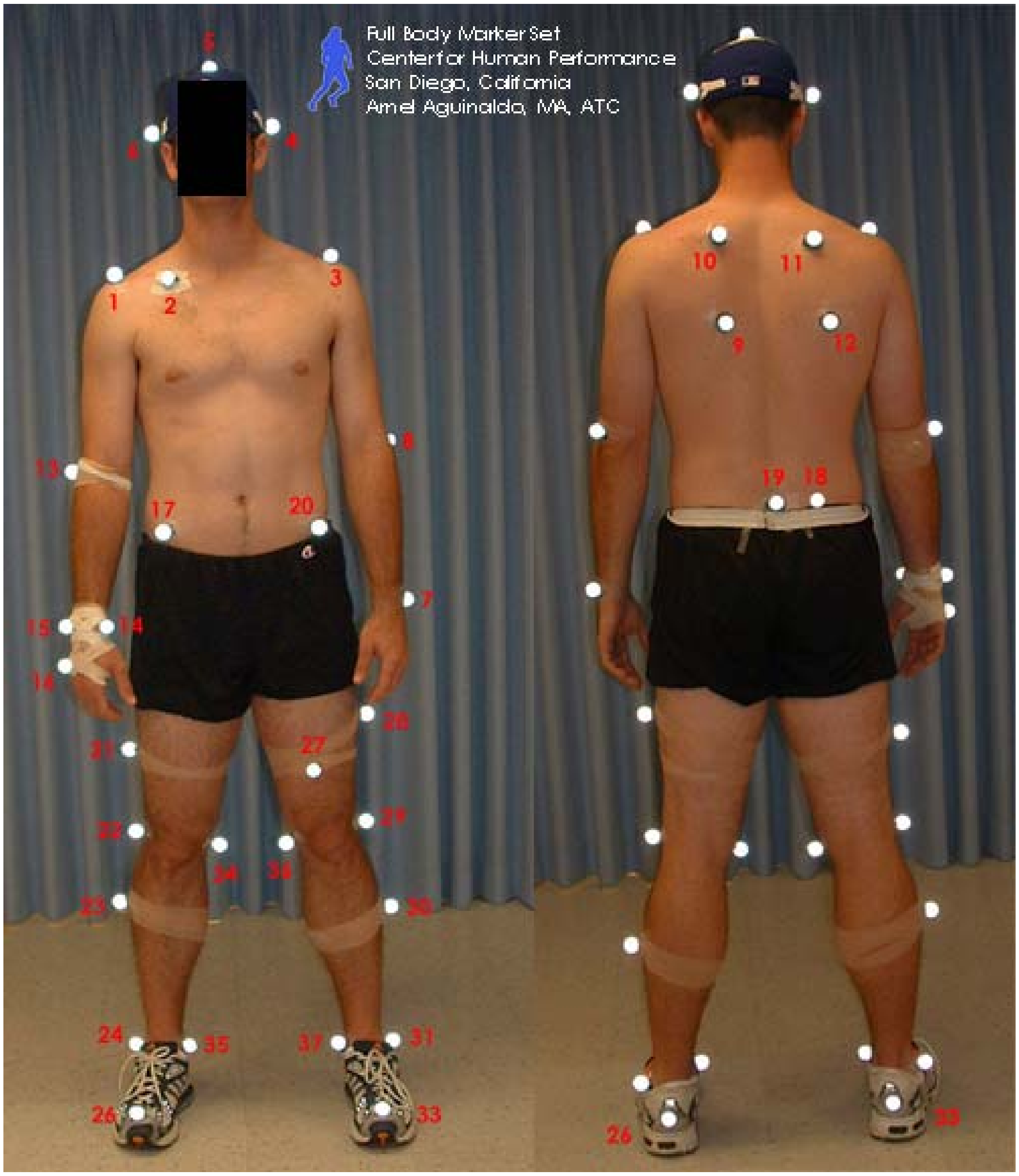

Figure 2.5 San Diego Center for Human Performance marker setup (Aguinaldo, 2005)

Figure 2.6 Combined ASMI and MRI reflective marker setup

The remaining studies are all derived from the American Sports Medicine Institute in Birmingham, Alabama. Therefore the marker system applied in each study remained consistent. Fleisig et al. (1996b, 1999, 2006) and Stodden et al. (2005) used 2.5 centimeter diameter reflective markers placed bilaterally on the following locations: proximal end of the third metatarsal, lateral malleolus, lateral femoral epicondyle, greater femoral trochanter, lateral superior tip of the acromion, and lateral humeral epicondyle. A reflective band was wrapped around the wrist of the throwing arm to designate the joint center for the wrist. This reflective marker setup can be seen in Figure 2.7. All of these markers have been placed to define the joint centers of each specific joint where calculations took place.

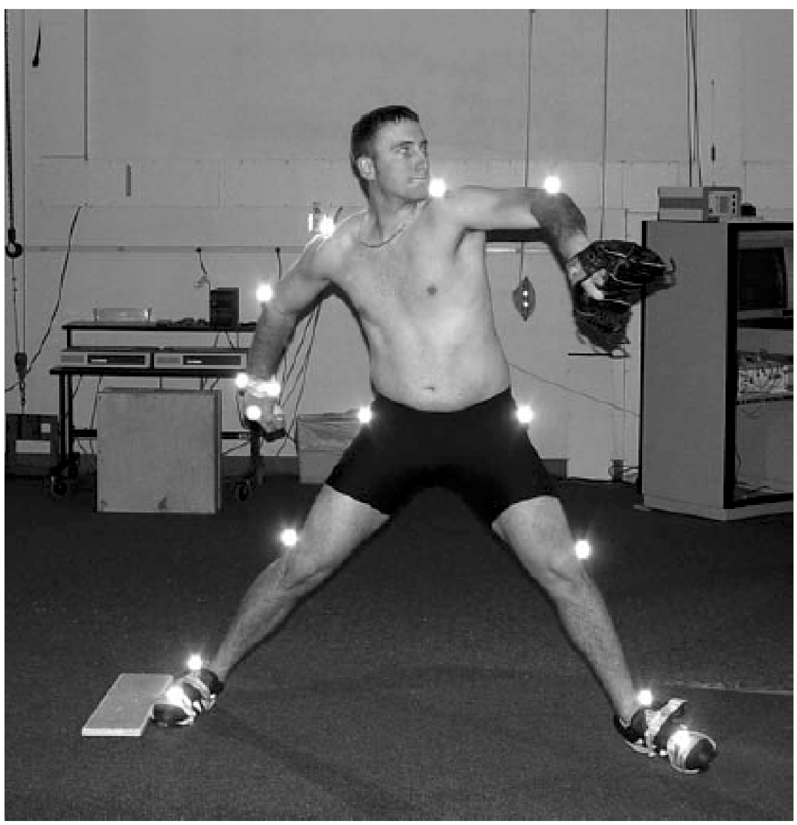

Figure 2.7 ASMI reflective marker setup (Fleisig et al. 2006)

CHAPTER III

MATERIALS AND METHODS

3.1 Experimental Methods

Five healthy male collegiate baseball pitchers (age, 19.2 ± 1 year; mass, 86.2 ± 7.9 kg; height, 1.87 ± 0.08 m) were studied. All five subjects threw right-handed. The pitchers were recruited on a volunteer basis at the American Sports Medicine Institute in Birmingham, Alabama. Prior to any activity, a questionnaire and informed consent form were read and filled out by the participant. The subject was then instructed to change into an outfit consisting of spandex shorts and tennis shoes. The subject's radius and humerus lengths of the arm were measured and recorded in centimeters. Also recorded were the waist size (pant waist size) and shoe size of each subject. In compliance with the University of Akron's Institutional Review Board for the Protection of Human Subjects, all of the data were collected at a prior date and were used as second-hand data for the investigator of this study (Appendices A-C).

Data collection took place at the American Sports Medicine Institute in Birmingham, Alabama. The laboratory setup appeared as in Figure 3.1. Eight, 3-D, high-speed, infrared cameras (Eagle Analog System, Motion Analysis Corporation, Santa Rosa, California) were set up and angled to capture the reflective markers placed on the pitcher throughout his entire throwing motion.

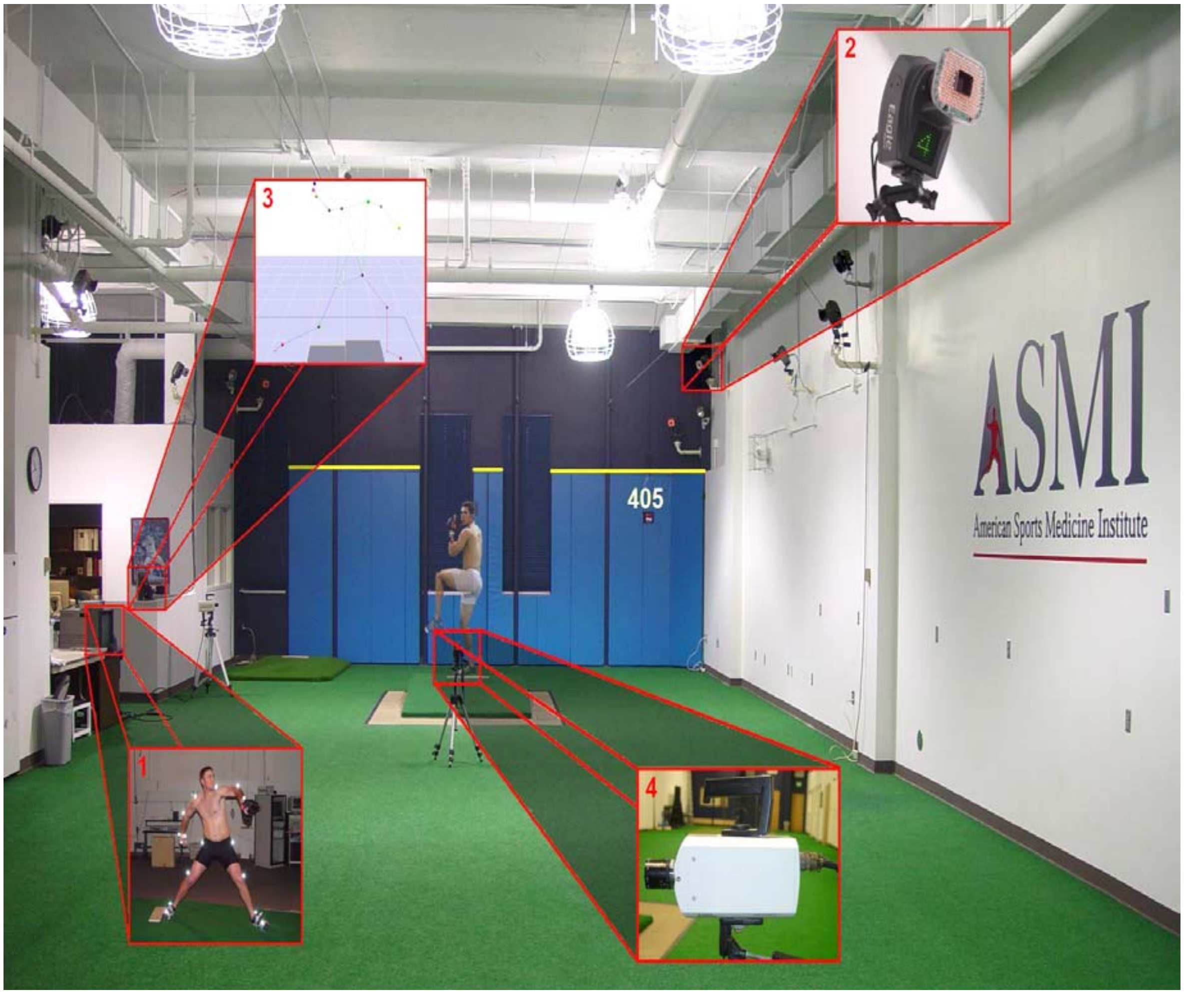

Figure 3.1 ASMI laboratory setup (American Sports Medicine Institute)

A calibration process was completed prior to subject arrival. In order to implement the direct linear transformation technique, a calibration procedure is required prior to any data collection (Zheng, Fleisig, Barrentine, & Andrews, 2004). At the American Sports Medicine Institute, the first calibration step used an L-frame with reflective markers attached at known global coordinates. Since these global coordinates are known, the data collected from the L-frame helps to calculate the cameras' positions. A secondary step of calibration is the "wand calibration." The wand is a one meter long rod with two markers attached at the ends and another marker in between, but off-center.

The wand calibration is performed to fill the entire capture volume thus expanding the calibrated area of the L-frame. This capture volume for baseball pitching included all areas where the pitcher's hands and feet may be present at any point during the pitching motion. From the wand calibration, the initial camera positions calculated during the L-frame calibration were refined. The position of each camera in space and its orientation in space relative to the global coordinate system was then determined.

Forty-six reflective markers (2.5-cm diameter) were placed on the subject to account for both marker systems used in this study (Fleisig et al. 2006). The ASMI method placed markers bilaterally on the proximal end of the third metatarsal, lateral malleolus, lateral femoral epicondyle, greater femoral trochanter, lateral superior tip of the acromion, and lateral humeral epicondyle. A marker was also placed on the ulnar styloid of the glove hand. Additional reflective markers were placed on the ulnar styloid, radial styloid, and distal end of the third metacarpal of the throwing hand to determine wrist and forearm motions.

In addition to the ASMI marker set, the markers used for the MRI method were applied at the same time to ensure that the pitching motion was recorded for both marker sets. The markers used for the MRI method incorporated the 16-markers described earlier from the ASMI method, and added an additional 30 markers to bring the total marker count up to 46. Marker identification for the two methods is shown in Table 3.1. The last two markers in Table 3.1 (right and left shoulder front) were static markers placed on the subject for a static trial only, and were then removed prior to data collection of the pitching motion. The static trial markers allow for body dimensions to be recorded and calculated during a stand-still trial.

Table 3.1 ASMI and MRI marker identification

RIGHT HANDED Markers Relative to Pitcher		
ASMI ID	ASMI Name	MRI ID
1	Leading hip	40
2	Leading shoulder	6
3	Throwing shoulder	5
4	Throwing elbow	27
5	Throwing medial wrist	32
6	Throwing lateral wrist	31
7	Throwing hip	39
8	Leading elbow	30
9	Leading wrist	34
10	Throwing knee	41
11	Throwing ankle	43
12	Throwing toe	23
13	Leading knee	42
14	Leading ankle	44
15	Leading toe	24
16	Throwing hand	35
17	Back head	1
18	Top head	2
19	Front left head	4
20	Front right head	3
21	Front torso	7
22	Left shoulder back	8
23	Back upper torso	9

RIGHT HANDED Markers Relative to Pitcher		
ASMI ID	ASMI Name	MRI ID
24	Right shoulder back	10
25	Back right torso	12
26	Back left torso	11
27	Front waist right	13
28	Front waist left	14
29	Back waist left	15
30	Back waist right	16
31	Right lower leg right	17
32	Right lower leg front	18
33	Left lower leg front	19
34	Left lower leg left	20
35	Right foot back	21
36	Right foot right	22
37	Left foot left	25
38	Left foot back	26
39	Right upper arm	28
40	Left upper arm	29
41	Left wrist lateral	33
42	Left hand	36
43	Left glove fingers	37
44	Left glove thumb	38
45	Right shoulder front	45
46	Left shoulder front	46

After completion of the subject's normal warm-up routine, data from each pitcher were recorded while he was throwing on an indoor pitching mound (Athletic Training Equipment Company, Santa Cruz, Arizona) to a net with a strike zone above home plate located the regulation distance away (18.44 m). Each subject was asked to throw 10 fastballs from the wind-up. One pitcher however, was not comfortable throwing from the wind-up and therefore threw his 10 pitches from the stretch. The results of pitching from the stretch instead of the windup would not make a difference in the kinematic values according to Escamilla et al. (2007). The motions of the reflective markers on each pitcher were captured by the 8-camera, high speed (240-Hz), automatic digitizing system (Motion Analysis Corporation, Santa Rosa, California) mentioned previously. Position data for these markers were then filtered with a 13.4-Hz low-pass filter. Joint center locations were calculated for each frame from significant anatomical landmarks.

Initial position data recorded by the cameras were processed using EVaRT software (Motion Analysis Corporation, Santa Rosa, California). Markers were first identified based on anatomical location. Once the markers had been identified, the three-dimensional coordinates of each marker were calculated using the direct linear transformation technique (Abdel-Aziz et al. 1971). This was followed by an interpolation process ensuring that all the reflective markers were captured by the cameras for all of the relevant frames associated with the pitching motion. These frames started from maximum knee height until a few frames after follow-through was complete. After the 44 markers were identified for all the frames, the global three-dimensional coordinates established by the EVaRT software were used to calculate the joint centers and kinematic parameters associated with the pitching motion mechanics.

Eleven position parameters were calculated for each pitch. These parameters were shoulder abduction, shoulder horizontal abduction, shoulder external rotation, knee flexion, and elbow angle at the instant of lead foot contact. Lead foot contact was determined by an algorithm to be the last frame before the ankle's velocity decreased to less than 1.5 m/s (Fleisig 1994). Maximum values of shoulder horizontal abduction, shoulder external rotation, and elbow angle were calculated during the pitching motion. Additionally, trunk flexion, shoulder horizontal abduction, and elbow angle at the instant of ball release were determined. Ball release was determined to correspond to the second motion analysis frame after the throwing forearm passed the vertical plane, or when the wrist joint center passed the elbow joint center in the global X-direction towards home plate (Fleisig 1994). Ball velocity was measured and recorded for each pitch thrown by a Jugs Tribar Sport radar gun (Jugs Pitching Machines Co., Tualatin, Oregon).

3.2 Theoretical Methods

Raw data from the EVaRT software provided the global coordinates for all of the markers attached to the subject's body. For frames missing certain marker locations, an interpolation process was performed to provide three-dimensional coordinates for the marker in each missing frame. Data was analyzed from maximum knee height until the completion of the follow-through motion of the subject's pitching mechanics.

Reference frames were set up for not only a global reference frame, but also the trunk and elbow (Fleisig et al. 1996, Figures 3.2 and 3.3).

Global Reference Frame

Up: Z_G = vertical direction

Left: $Y_G = Z_G \times$ [a vector from the pitching rubber to home plate]

Forward: $X_G = Y_G \times Z_G$

Trunk Reference Frame

Lateral: Z_t = vector from leading shoulder marker to midshoulder

Anterior: X_t = [vector from midhip to midshoulder] $\times Z_t$

Superior: $Y_t = Z_t \times X_t$

Elbow Reference Frame

Distal: Z_e = vector from throwing elbow marker to throwing wrist

Medial: $X_e = Z_e \times$ [vector from shoulder joint center to elbow marker]

Anterior: $Y_e = Z_e \times X_e$

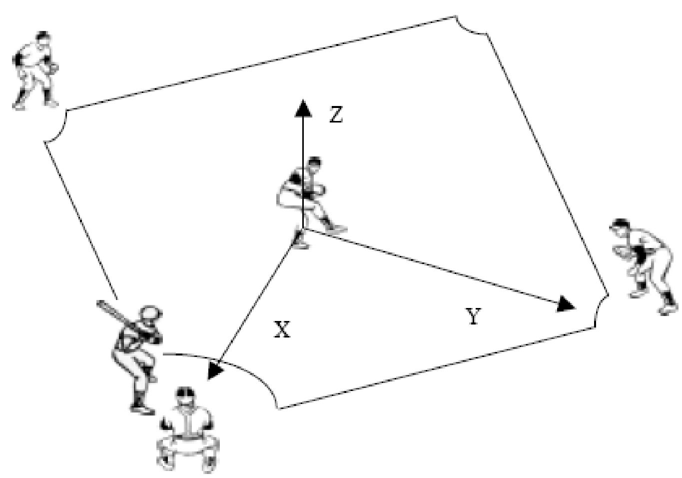

Figure 3.2 Global reference system for baseball pitching (Zheng et al. 2004)

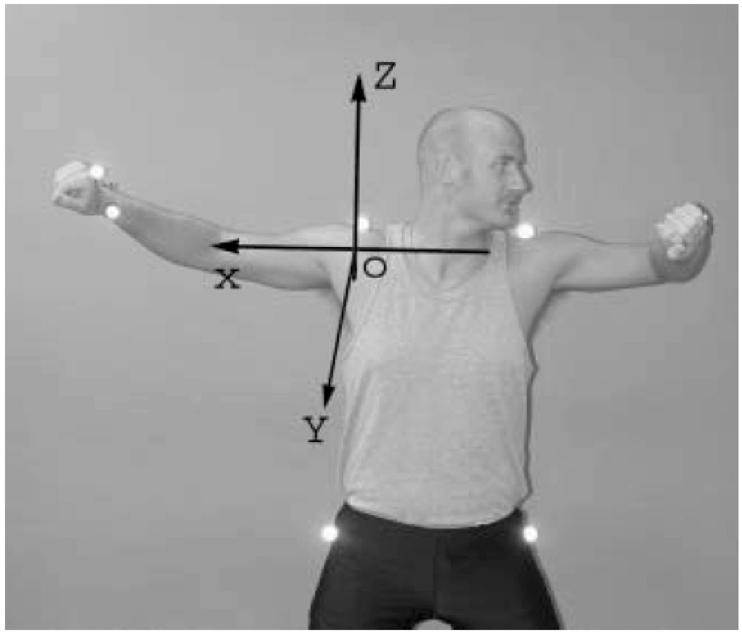

Figure 3.3 Local reference system at the throwing shoulder (Zheng et al. 2004)

The ASMI method incorporates equations that were developed by Dillman et al. (1993) to calculate the joint center location from the markers based on the subject's humerus ($l_{humerus}$) and radius (l_{radius}) lengths which were obtained prior to pitching (Fleisig et al. 1996, Zheng et al. 2004). The distance between the shoulder joint center and the actual marker on the tip of the acromion was ($0.019 + l_{humerus} / 6.05$). 0.019 refers to the radius of the reflective markers in meters used in the study and 6.05 is a correlation coefficient associated with humeral length to define the joint center. The directions for each component of this vector, with respect to the trunk, were 0.121 in the lateral direction (x-direction), 0.413 in the anterior direction (y-direction), and 0.903 in the inferior direction (z-direction). The average direction for this vector was ($0.413 \cdot$ armflag, -0.903, 0.121), where armflag was 1 for right-handed pitchers and -1 for left-handed pitchers. Therefore the average vector from marker to joint center can be calculated as,

$$S_{m\text{-}jc} = (0.019 + l_{humerus} / 6.05) \cdot (0.413 \cdot \text{armflag}, -0.903, 0.121).$$

The vector from the shoulder marker to the joint center was then calculated by multiplying the local reference frame for the trunk by the vector from shoulder marker to joint center,

$$[(S)] = [(X_t)(Y_t)(Z_t)]\ [(S_{m\text{-}jc})].$$

Finally, the shoulder joint center position was calculated,

$$(\text{Shoulder joint center position}) = (\text{Shoulder marker position}) + (S).$$

Similarly, the elbow joint center was calculated via an adjustment. The distance between the elbow joint center and the marker placed on the lateral humeral epicondyle was $(0.019 + l_{radius} / 8.70)$. The directions for the vector are 0.800 in the medial direction (x-direction), 0.521 in the anterior direction (y-direction), and 0.296 in the distal direction (z-direction). The average direction for the elbow vector was (0.800 · armflag, 0.521, 0.296). Therefore the average vector from elbow marker to joint center was calculated as,

$$E_{m\text{-}jc} = (0.019 + l_{radius} / 8.70) \cdot (0.800 \cdot \text{armflag}, 0.521, 0.296).$$

The local elbow reference frame determined by the reflective markers and the shoulder joint center was then used to calculate the vector finding the elbow joint center.

$$[(E)] = [(X_e)(Y_e)(Z_e)]\ [(E_{m\text{-}jc})]$$

After calculating the vector E, elbow joint center was determined for the subject.

$$(\text{Elbow joint center position}) = (\text{Elbow marker position}) + (E)$$

The wrist joint center was simply determined by calculating the midpoint between the radial styloid and ulnar styloid markers.

The MRI method for obtaining joint center coordinates incorporates the method of generalized coordinates (N. Madsen, personal communication, July 3, 2006). Generalized coordinates are a collection of variables which ultimately specify the location of every particle associated with the mechanical system being dealt with. For a single rigid body that is free to move in three dimensions, six generalized coordinates are required to know not only location, but orientation. Generally, an origin fixed in the body is selected, and three generalized coordinates specify the location of its origin. Then a set of three orthogonal axes fixed within the body are selected. The coordinates of a particle in the body relative to the fixed axes are referred to as local coordinates and have a fixed position in a rigid body. The orientation of the body-fixed axes relative to the global axes can be specified by three angles, commonly known as Euler angles. Therefore, the body origin location is determined by the first three generalized coordinates, and the orientation of the body-fixed axes is determined by the second set of three generalized coordinates. Then one can use the local coordinates of any point in the rigid body to determine the global position of that specific point.

For example, a typical ball and socket joint such as the hip, fixes one point of the connected body relative the other point, but allows the connected body to freely rotate about that point (N. Madsen, personal communication, July 3, 2006). This means that this type of system has nine generalized coordinates. Six coordinates are required to locate and orient the first rigid body. The additional three coordinates are then needed to orient the connected body relative to the first body that was previously defined. Thus, this system has three translation variables and three rotational variables for the first rigid body, and then another three rotational variables for the connected body relative to the original rigid body. From these generalized coordinates, any point on the pelvis or femur can now be defined.

A 3-D model of the lower body using generalized coordinates modeled the skeleton as a 10-segment, 23 degree of freedom model (Shelburne, Pandy, Anderson, & Torry, 2004). The number of degrees of freedom associated with each joint is the key characteristic needed to determine the number of generalized coordinates required. Ball and socket joints have three degrees of freedom, universal joints, such as the ankle, have two degrees of freedom, and hinge joints like the elbow and knee only have one degree of freedom.

The first step in the Motion Reality approach was to develop a model of the system of interest, the baseball pitcher (N. Madsen, personal communication, July 3, 2006). From the model, the number of generalized coordinates was determined based on the number of rigid bodies. Then a preliminary scaling capture was done to establish the actual dimensions of each subject. During this stage, the local coordinates of each marker relative to the rigid body to which it was attached was determined. Following motion capture, the generalized coordinates were used from each frame to determine the position of each and every point of interest for the model. Therefore, joint centers can be calculated by knowing the basic anatomical structures and where joint centers are generally estimated relative to those structures.

Once all the joint centers were approximated, kinematic values were calculated for both methods based on the angles formed by vectors set up at the joint centers.

Shoulder kinematic quantities had their own unique angle setups (Zheng et al. 2004). Shoulder abduction can be defined as the angle between the humerus and the inferior direction of the trunk in the frontal plane. This inferior direction for the trunk is represented by a line connecting the midpoint of the two shoulder markers and the midpoint of the two hip markers. Shoulder horizontal adduction is the angle between the humerus and the line connecting the two shoulder markers in the trunk's transverse plane. Finally for the shoulder joint, external rotation can be quantified by the rotation of the upper arm about its own long axis. Equations for the specific kinematic parameters can be found in Appendix D.

The other three measurements, elbow angle, knee angle, and trunk flexion, also have defined characteristics to calculate the angles formed. The elbow flexion angle can be defined by the upper arm and forearm vectors along their long axes. Knee flexion is also determined by the long axes of the two body segments associated with the knee joint, the femur and tibia. Trunk flexion is described by the shoulder and hip markers which creates the trunk vector in the global coordinate system.

CHAPTER IV

RESULTS AND DISCUSSION

Using the previously described methods, the eleven kinematic variables were examined and compared for each method in this study. For each subject, a mean and standard deviation were calculated, and outlier data were removed from the data set due to errors in calculating the desired parameter. Outlier data were determined to be any values that were greater than 1.5 times the interquartile range away from the respective upper and lower quartile values for each parameter tested. An average and standard error of the mean were calculated for a combination of all five pitchers data within each kinematic parameter (Table 4.1 through 4.3). In agreement with Fleisig et al. 2006, the ASMI kinematic results fell within the deviations of each calculated angle.

The maximum shoulder horizontal adduction and maximum shoulder external rotation angles were determined by locating the greatest magnitude of each angle during the pitching motion cycle from the kinematic data on the respective angle profiles for each trial. Examples of the maximum profiles are shown in Figures 4.1 and 4.2. The remaining angles were calculated at the temporal parameters of foot contact and ball release, using the methods previously described (Figures 4.3 through 4.6).

From the five subjects, a total of 44 pitches were used in the statistical database. The average velocity for all pitchers was 34.6 ± 0.6 m/s. Statistical testing was

Table 4.1 Average results at foot contact for all subjects

Kinematic Parameter	ALL SUBJECTS ASMI	ALL SUBJECTS MRI
	(n=44)	
Foot Contact		
Shoulder Abduction	97.10 ± 1.23	103.27 ± 1.63
Shoulder Horizontal Adduction	-10.73 ± 1.75	-7.30 ± 2.41
Shoulder External Rotation	44.70 ± 4.09	42.78 ± 4.55
Knee Flexion	46.30 ± 1.02	50.99 ± 1.47
Elbow Flexion	70.18 ± 2.70	61.83 ± 3.07

ASMI – American Sports Medicine Institute
MRI – Motion Reality Inc.

Table 4.2 Average results at ball release for all subjects

Kinematic Parameter	ALL SUBJECTS ASMI	ALL SUBJECTS MRI
	(n=44)	
Ball Release		
Trunk Flexion	30.27 ± 1.00	28.85 ± 0.86
Elbow Flexion	24.17 ± 1.30	15.53 ± 1.65
Shoulder Horizontal Adduction	11.98 ± 1.57	0.39 ± 1.40

Table 4.3 Average results at maximum values for all subjects

Kinematic Parameter	ALL SUBJECTS ASMI	ALL SUBJECTS MRI
	(n=44)	
Maximum Values		
Maximum Shoulder Horizontal Adduction	20.03 ± 1.56	17.41 ± 2.21
Maximum Shoulder External Rotation	173.54 ± 1.22	178.65 ± 1.88
Maximum Elbow Flexion	19.43 ± 0.71	8.83 ± 1.34
Ball Velocity (m/s)	34.6 ± 0.6	

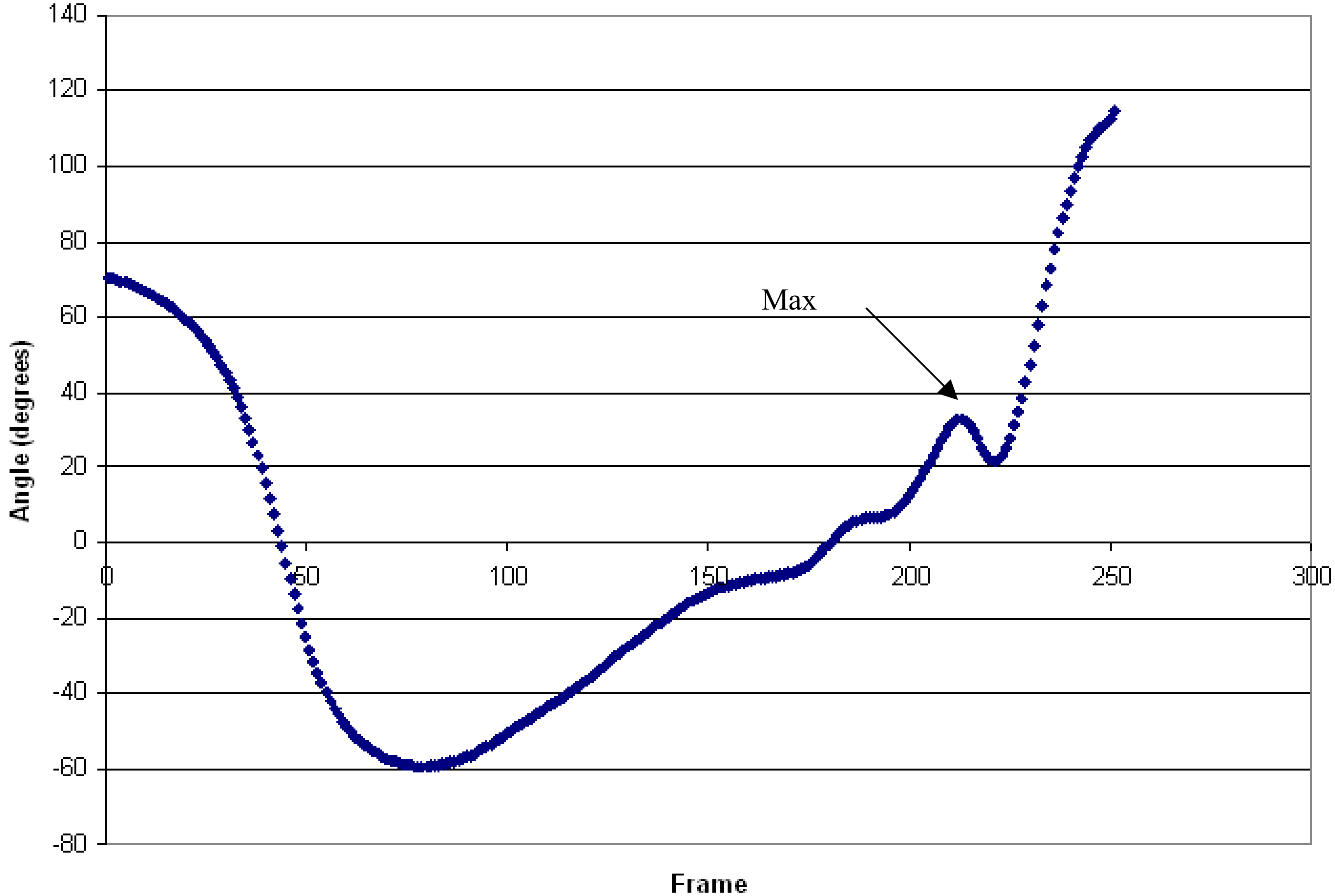

Figure 4.1 Maximum shoulder horizontal adduction profile for subject 1, trial 1 (rb2431)

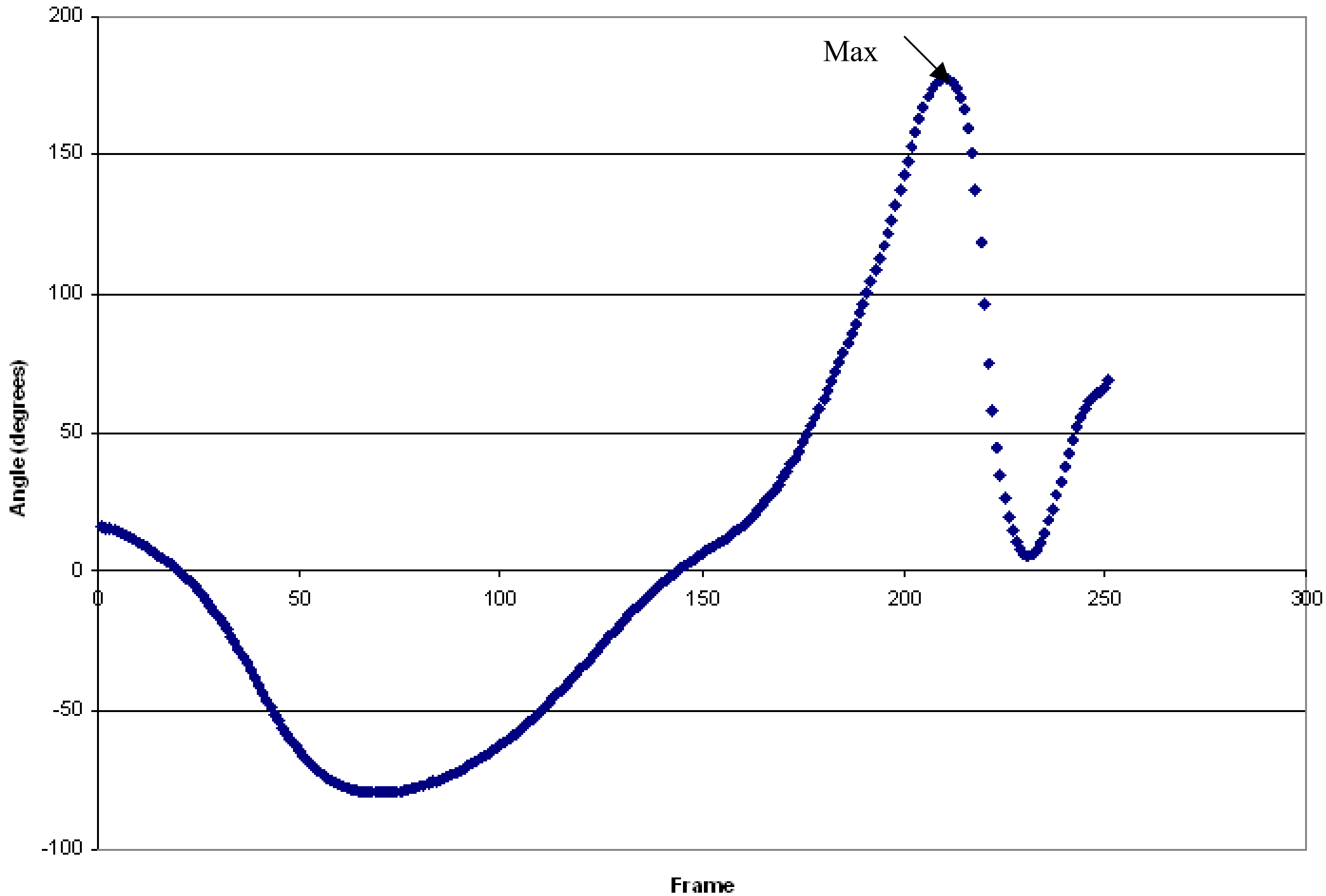

Figure 4.2 Maximum shoulder external rotation profile for subject 1, trial 1 (rb2431)

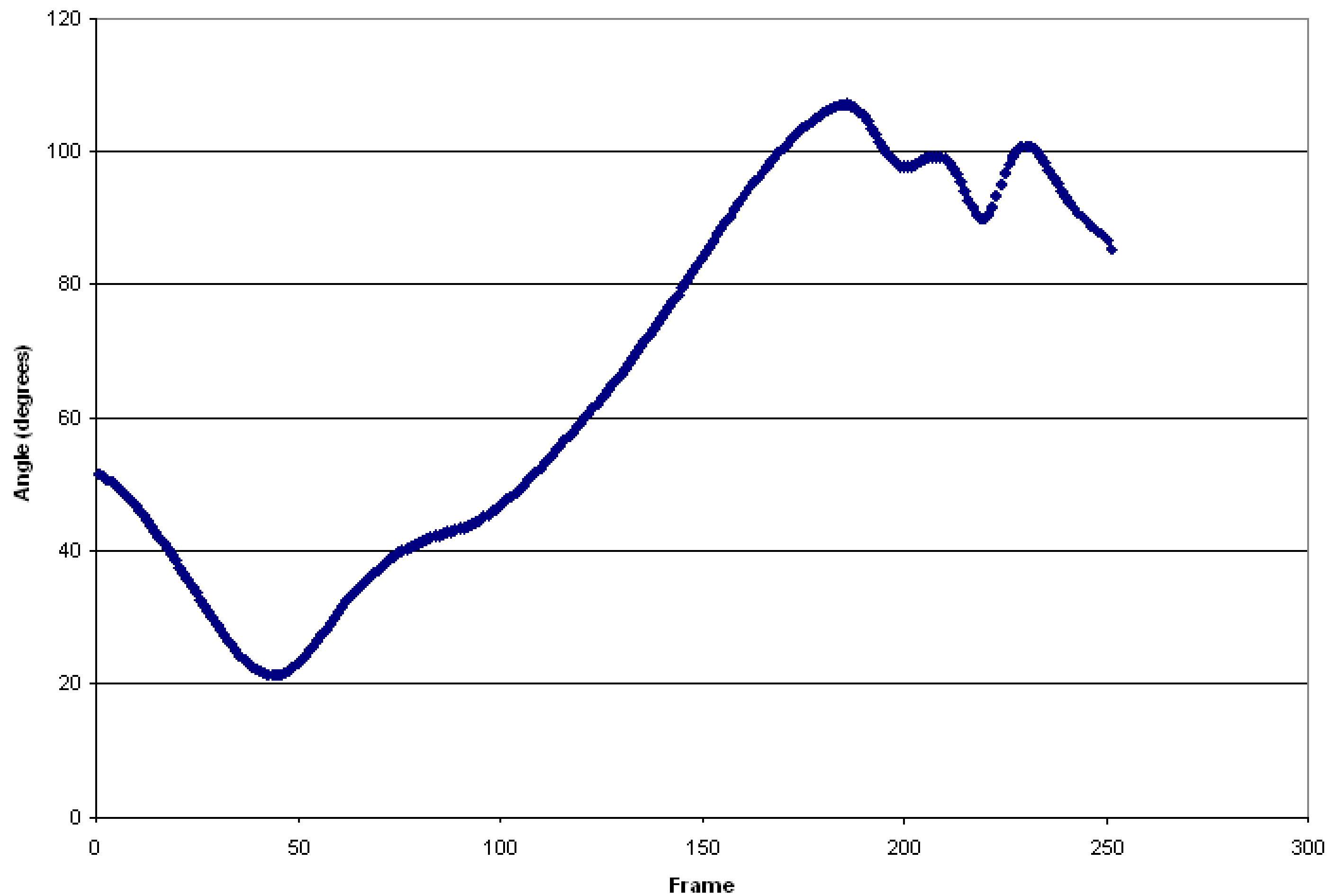

Figure 4.3 Shoulder abduction profile for subject 1, trial 1 (rb2431)

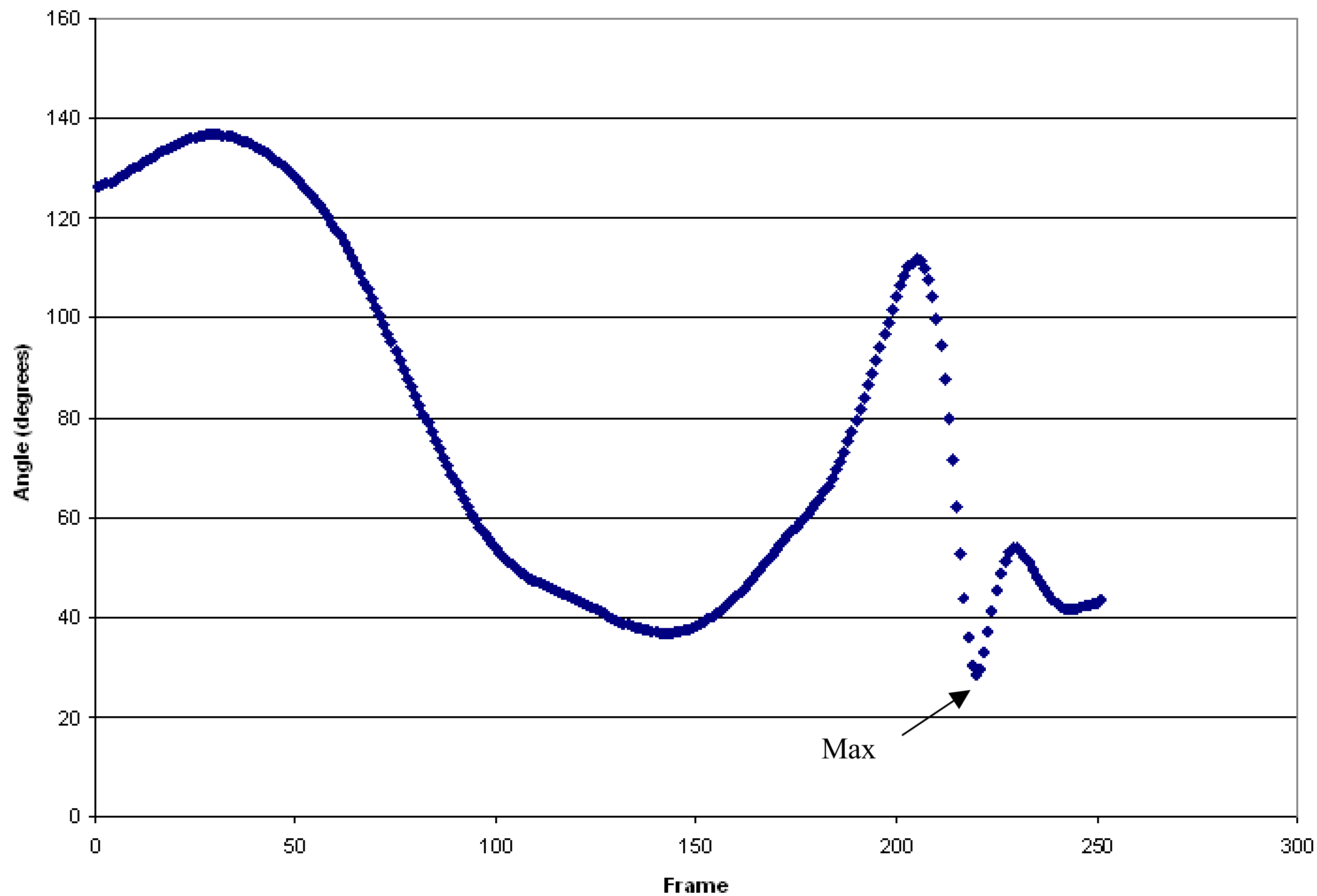

Figure 4.4 Elbow flexion profile for subject 1, trial 1 (rb2431)

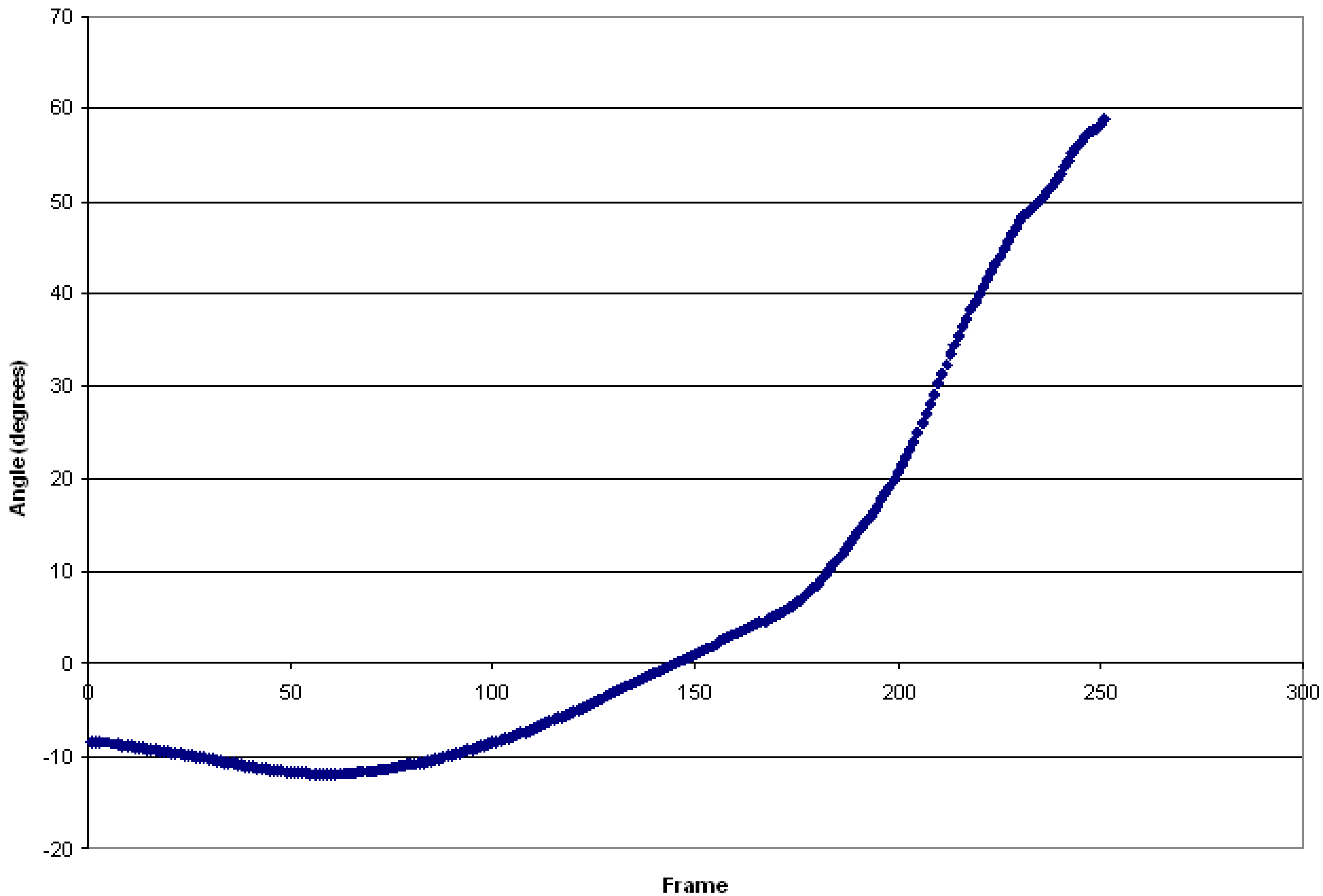

Figure 4.5 Trunk flexion profile for subject 1, trial 1 (rb2431)

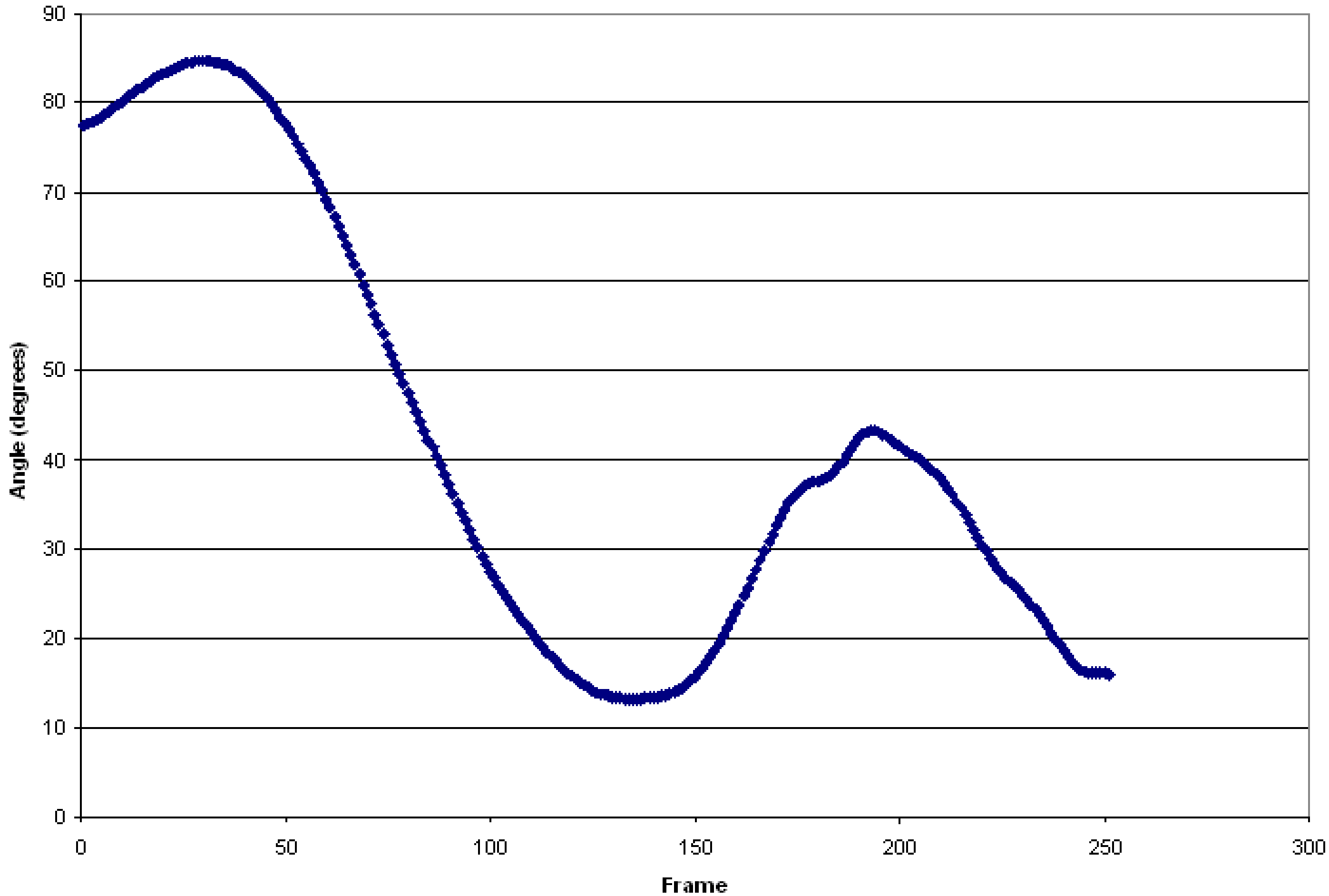

Figure 4.6 Knee flexion profile for subject 1, trial 1 (rb2431)

performed on each subject for all eleven kinematic parameters. Comparison between the two marker methods was completed using a paired t-test ($\alpha = 0.05$). The statistical results determined whether or not there was a significant difference between the two methods for calculating the joint centers and kinematic parameters.

There were only two parameters that were not significantly different from one another. Using the paired t-test calculation, shoulder external rotation at foot contact ($t < t_{critical}$, $0.7330 < 2.023$) and maximum shoulder horizontal adduction ($t < t_{critical}$, $0.8595 < 2.025$) were the only kinematic parameters that had no significantly different results between the two methods. This would allow for acceptance of the null hypothesis that stated there would not be a significant statistical difference between the two methods. However, when looking at the individual subject data, there were differences of at least ten degrees for three of the five subjects within each parameter. This would not be acceptable in the realm of clinical significance. For the kinematics of baseball pitching, a difference of five degrees or greater would mean that the two parameters were clinically significantly different according to clinicians at the American Sports Medicine Institute (G. Fleisig, personal communication, July 21, 2006). Such a difference could result in improper mechanics which could possibly lead to injury. In this case study, since over half of the subjects for both of the statistically not significant parameters had average differences of ten degrees or more, the statistical non-significance loses its credibility in the clinical environment.

For the remaining results at foot contact (shoulder abduction, shoulder horizontal adduction, knee flexion, and elbow flexion), all rotations were significantly different when comparing the two methods. Maximum external rotation and maximum elbow flexion were also determined to be significantly different via the paired t-test. Finally, the kinematic parameters at ball release (trunk flexion, elbow flexion, and shoulder horizontal adduction) were also all significantly different between the two methods.

From a clinical standpoint, only trunk flexion at ball release could be determined to be clinically not significant between the two methods. All five subjects had their average individual data within a five degree difference and the average data for all five subjects combined was also within five degrees of separation. The rest of the kinematic parameters had at least two of the five subjects or the combination of all five subjects with average differences of greater than five degrees meaning that their results were clinically significantly different.

No trend was observed between the two methods of having one of the methods consistently producing a lesser angle or greater angle than the other. For each parameter, there was a variable difference between the two methods among each subject. The ASMI method appeared to have more consistent results due to the fact that the standard deviations for each kinematic parameter were generally less than the standard deviations observed using the MRI method of calculating. The large standard deviation values are acceptable due to individual adaptation for each pitcher. Each pitcher's motion will be different from one another based on what feels comfortable and easier for the pitcher throwing.

Since the two methods did not yield comparable results, in order to determine which method is producing more accurate results, future research should involve using each marker system to calculate known body angles. For example, a goniometer could be used when the body is placed at a certain angle. When the body is placed at this angle, the pose should be captured while the markers are present on the body and then calculations should be performed for angle determination. Therefore a more accurate angle value could be compared to the calculated angles using each of the two reflective marker methods. Also, x-rays may be used to help give more accurate results when looking for joint centers, followed by angle determination. In addition, future research should involve more subjects to make this a truly robust experiment. According to calculations involving true standard deviations and the smallest true differences that should be detected, along with the significance level of $\alpha = 0.05$ and the power of the test ($P = 0.80$), an acceptable sample size for this project would require at least 35 subjects. Furthermore, in order to control variation, this study investigated only right-handed collegiate pitchers. In reality, pitchers also may throw left-handed, so it would be important to see how the results would differ for this different group of pitchers. Since the pitching motion revolves around a summation of forces, looking at the lower body kinematics would also be an interesting study, because there is a different approach toward joint center calculation between the two methods. The ASMI method assumes the markers themselves represent the joint centers for the lower body joints, whereas the MRI method calculates the actual joint centers.

CHAPTER V

SUMMARY AND CONCLUSIONS

Kinematic values were determined at various points in the pitching motion sequence for five collegiate baseball pitchers. A total of 44 pitches were analyzed from these five subjects, with each subject having between 7 to 10 acceptable trials for data calculation. The subjects' body motions were recorded using eight, 3-D, high-speed, infrared cameras (Eagle Analog System, Motion Analysis Corporation, Santa Rosa, California) to capture the reflective markers placed on the pitcher throughout his entire throwing motion. Joint centers were approximated for the two different methods of marker application. From the joint center calculations, body angles were calculated at instances of foot contact, ball release, and maximum values of shoulder horizontal adduction, shoulder external rotation, and elbow flexion. Outlier data were removed from both methods following data calculations. A paired t-test was the method of statistical testing performed on the final kinematic quantities, and these tests determined that only shoulder external rotation at foot contact and maximum shoulder horizontal adduction can be deemed not statistically different. However, there was a significant clinical difference between the two methods. Significant clinical difference was set at a difference of greater than five degrees of separation for any kinematic parameter based upon previous clinical research at the American Sports Medicine Institute. A difference of more than five degrees could significantly alter the biomechanics of the pitching motion, which could lead to possible injury. The remaining nine parameters all had deviations to such an extent that the results were significantly different. Overall, these results would allow for rejection of the null hypothesis, which stated that there would not be a significant statistical difference between the calculations for joint centers and the kinematic parameters determined using the marker systems designed by ASMI and MRI.

In summary, the findings from this study showed that comparing kinematic data from the two marker methods would not produce consistently comparable results. Instead, the two methods yield significantly different kinematic values. It is unclear however, as to which method truly describes the correct body angle. For the time being, data results should not be compared directly between the two marker methods. Future researchers should adhere to one of the two methods until more conclusive results are determined as to which method more accurately depicts the desired kinematic variables.

Baseball pitching mechanics have recently become a major concern to athletes and engineers due to the significant increase in the number of pitching injuries and surgeries that have occurred over the last several years. This study aimed to investigate the relationship between two reputable methods that are used today to measure the kinematics of the pitching motion. The results from this study indicate that the two methods produce significantly different kinematic results and therefore cannot be replaced by one another. Future researchers may use the data from this study to help establish a uniform protocol and reflective marker system for quantifying the biomechanics of the pitching motion.

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APPENDICES

APPENDIX A

INSTITUIONAL REVIEW BOARD FOR THE PROTECTION OF HUMAN SUBJECTS RESEARCH APPROVAL FORM

This appendix contains the Institutional Review Board for the Protection of Human Subjects research approval form granted by the University of Akron. This IRB form ensures that the protocol used for this project met all the guidelines and safety requirements involving research with human subjects.

Office of Research Services and Sponsored Programs
Akron, OH 44325-2102
(330) 972-7666 Office
(330) 972-6281 Fax

November 13, 2006

Matthew Streicher
4779 Sentinel Drive
Brecksville, Ohio 44141

Mr. Streicher:

The University of Akron's Institutional Review Board for the Protection of Human Subjects (IRB) completed a review of the protocol entitled "*Kinematic Comparison of Marker Set Techniques Used in Biomechanical Analysis of the Pitching Motion*". The IRB application number assigned to this project is **20061104.**

The protocol was reviewed on November 10, 2006 and qualified for exemption from continuing IRB review. The protocol represents minimal risk to subjects and matches the following federal category for exemption:

> *(4) Research involving the collection or study of existing data, documents, records, pathological specimens, or diagnostic specimens, if these sources are publicly available or if the information is recorded by the investigator in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects.*

Annual continuation applications are not required for exempt projects. If you make any changes or modifications to the study's design or procedures that either increase the risk to subjects or include activities that do not fall within one of the categories exempted from the regulations, please contact the IRB **first**, to discuss whether or not a request for change must be submitted. Any such changes or modifications must be reviewed and approved by the IRB prior to their implementation.

You are required to submit a Final Report to the IRB, upon completion of this research.

Please retain this letter for your files. If the research is being conducted for a master's thesis or doctoral dissertation, the student must file a copy of this letter with the thesis or dissertation.

Sincerely,

Sharon McWhorter
Interim Director

Cc: Mary Verstraete, Advisor
Rosalie Hall, IRB Chair

APPENDIX B

INFORMED CONSENT FORM

This appendix contains the consent form supplied by the American Sports Medicine Institute. Each subject was required to sign this consent form prior to any collection of data. By signing this form, each subject granted permission to use any information collected during the research procedure for the benefit of this project.

AMERICAN SPORTS MEDICINE INSTITUTE
JAMES R. ANDREWS, M.D. BIOMECHANICS LABORATORY

CONSENT FORM - THROWING ANALYSIS

I, ____________________________, having attained my nineteenth birthday and otherwise having full capacity to consent, do hereby volunteer to participate in a study titled *Biomechanical Analysis of Throwing*, throwing analysis under the direction of Glenn Fleisig, Ph.D. ASMI and St. Vincent's Fitness Center accept no responsibility for any injury I incur while throwing or exercising.

The implications of my voluntary participation, the nature, duration, and purpose; the methods and means by which the study is to be conducted; and the inconveniences and hazards to be expected have been thoroughly explained to me. I have been given an opportunity to ask questions concerning this investigation and these questions have been answered to my complete satisfaction. Any data generated from this test including photographs and video taken during the test may be used for future research studies, the ASMI website, and/or presentations.

I understand that I may, at any time during the course of this investigation, revoke my consent and withdraw from the study without prejudice.

____________________________________ ____________________

Signature Date

(Parent or custodian if under 19 years of age)

APPENDIX C

BIOMECHANICAL ANALYSIS QUESTIONNAIRE

This questionnaire was filled out by each subject prior to any throwing or activity involved with this project. Basic anthropometric data is collected on this form as well as a survey of past injury and past performance on the baseball field.

American Sports Medicine Institute
Biomechanical Analysis Questionnaire

Demographic Information:

- **Name:______________________________ Date:_____________ Test #:________**
- **Address:____________________________ DOB:_____________ Age:________**

  ____________________________________ Phone #:(____)_____________________.
- **E-mail Address:______________________ Cell Phone #:(____)___________________.**
- **Height (in):_____ Weight (lbs):______ Humerus (cm):_______ Radius (cm):_______**
- **Waist Size:______ Shoe Size:_______**

Baseball Background:

- **Team/Organization:____________________ Coach:______________________**
- **Dominance: RH LH**
- **Level: Major Minor(AAA AA A IND) Collegiate JUCO High School**

  Youth League Recreational
- **Years Played Organized Baseball in Life:______ Years Pitched in Organized Baseball:_____**
- **How often do you work on pitching mechanics? ______/ week**
- **What types of exercises do you get during the season? Cardio/Upper Body/Lower Body/Tubing/Plyometric**
- **Average number of innings per game:_______**
- **Average number of pitches per game:________**
- **Average number of days between outings:________**
- **Typically used as a: Starting Pitcher Relief Pitcher Both**

Season	Dates	Level	Games	Innings	ERA	Wins	Losses	Saves	K's	BB's	Avg. Vel.	Peak Vel.
Current												
Previous												
Previous												
Previous												

- **Pre-Game Warm-Up: Bullpen:________pitches**

  Running:________poles/laps/sprints
- **Do you ever pitch in more than one league at a time? YES NO**
- **Out of every 10 pitches, how many would be:**

  FB______ CH______ CB______ SL______ SPLIT______ SINK_____ CUT-FB______
- **Age when began throwing:**

  FB______ CH______ CB______ SL______ SPLIT______ SINK_____ CUT-FB______

	Dates	Diagnosis	Time Missed	Treatment	Doctor
Shoulder Injury (non-surgical)					
Shoulder Surgery (procedure)					
Elbow Injury (non-surgical)					
Elbow Surgery (procedure)					
Other Injury (non-surgical)					
Other Injury (part & procedure)					

INJURY HISTORY

ASMI
American Sports Medicine Institute

APPENDIX D

KINEMATIC PARAMETER EQUATIONS

This appendix contains the vector equations used to calculate the specific kinematic parameters that were studied for this project. The angles that are discussed in this appendix include shoulder abduction, shoulder horizontal adduction, shoulder external rotation, elbow flexion, trunk flexion, and knee flexion.

Equations for adjusted markers (ASMI method) (Zheng et al. 2004):

Local coordinate system for shoulder

X-axis : $I_{sx} = (V_{sh\text{-}t} - V_{sh\text{-}l}) \,/\, |\, V_{sh\text{-}t} - V_{sh\text{-}l} |$

Y-axis : $I_{sy} = (I_{trunk} \times I_x) \,/\, |\, I_{trunk} \times I_x \,|$

Z-axis : $I_{sz} = I_{sx} \times I_{sy}$

$V_{sh\text{-}t}$ is the vector of the throwing shoulder in the global system

$V_{sh\text{-}l}$ is the vector of the leading shoulder in the global system

$I_{trunk} = (V_{sh\text{-}t} + V_{sh\text{-}l} - V_{hip\text{-}t} - V_{hip\text{-}l}) \,/\, |\, V_{sh\text{-}t} + V_{sh\text{-}l} - V_{hip\text{-}t} - V_{hip\text{-}l} \,|$

$V_{hip\text{-}t}$ is the vector of the hip on the throwing side

$V_{hip\text{-}l}$ is the vector of the hip on the leading side

$V_{el\text{-}t}$ is the vector of the throwing elbow

$V_{w\text{-}t}$ is the vector of the throwing wrist

$V_{ua\text{-}t} = V_{el\text{-}t} - V_{sh\text{-}t}$ is the vector for the upper arm

$V_{fa\text{-}t} = V_{w\text{-}t} - V_{el\text{-}t}$ is the vector for the forearm

$I_{uay} = (I_{trunk} \times V_{ua\text{-}t}) \,/\, |\, V_{ua\text{-}t} \,|$

$I_{uaz} = (V_{ua\text{-}t} \times I_{uay}) \,/\, |\, V_{ua\text{-}t} \,|$

Shoulder Angles

$\alpha = 180 - \cos^{-1} (V_{ua\text{-}t} \cdot I_{sz} \,/\, |\, V_{ua\text{-}t} \,|)$ Shoulder Abduction

$\beta = \tan^{-1} (V_{ua\text{-}t} \cdot I_{sy} \,/\, V_{ua\text{-}t} \cdot I_{sx})$ Shoulder Horizontal Abduction

$\gamma = \tan^{-1} (V_{fa\text{-}t} \cdot I_{uaz} \,/\, V_{fa\text{-}t} \cdot I_{uay})$ Shoulder External Rotation

Elbow Angle

$\theta = \cos^{-1} (V_{ua\text{-}t} \cdot V_{fa\text{-}t} \,/\, | V_{ua\text{-}t} | \cdot | V_{fa\text{-}t} |)$ Elbow Flexion

Trunk

$\xi = \tan^{-1} (I_{trunk} \cdot I_{gx} \,/\, I_{trunk} \cdot I_{gz})$ Trunk Flexion

Knee

Knee flexion is just measured by the angle formed from the vector connecting the hip and knee joint centers along the femoral long axis with the vector connecting the knee and ankle joint centers along the long axis of the tibia.

APPENDIX E

INDIVIDUAL AVERAGE RESULT TABLES

This appendix contains the data for each individual subject in a table format. The mean values and standard deviations for each subject within the eleven kinematic parameters studied within each method of calculation (ASMI or MRI) are included in the following tables. Also included within these tables are the means and standard deviations for ball velocity for each pitcher.

	rb2431			ga2435	
Kinematic Parameter	ASMI	MRI		ASMI	MRI
	(n = 7)			(n = 10)	
Foot Contact					
Shoulder Abduction	105.35 ± 1.83	107.75 ± 2.25		84.55 ± 0.83	90.88 ± 6.07
Shoulder Horizontal Adduction	-1.55 ± 2.92	3.07 ± 4.63		-3.53 ± 3.20	2.49 ± 1.88
Shoulder External Rotation	71.87 ± 5.67	70.55 ± 6.28		22.97 ± 21.18	34.92 ± 18.48
Knee Flexion	38.47 ± 2.38	49.44 ± 1.25		51.09 ± 3.62	57.35 ± 4.01
Elbow Flexion	62.50 ± 3.91	58.21 ± 3.27		43.16 ± 1.34	32.01 ± 1.83
Maximum Shoulder Horizontal Adduction	30.93 ± 0.73	20.64 ± 11.51		21.85 ± 0.94	6.64 ± 2.32
Maximum Shoulder External Rotation	181.60 ± 2.44	180.68 ± 6.32		161.24 ± 2.29	172.71 ± 2.96
Ball Release					
Trunk Flexion	39.37 ± 1.10	37.20 ± 1.95		21.30 ± 2.60	22.10 ± 2.94
Elbow Flexion	40.06 ± 3.16	35.28 ± 5.61		26.23 ± 1.65	14.92 ± 1.60
Shoulder Horizontal Adduction	22.62 ± 1.33	11.99 ± 1.19		17.12 ± 1.17	6.66 ± 2.37
Maximum Elbow Flexion	27.72 ± 0.61	22.31 ± 3.98		19.85 ± 0.95	4.48 ± 0.78
Ball Velocity (m/s)	35.76 ± 0.63			32.72 ± 0.66	

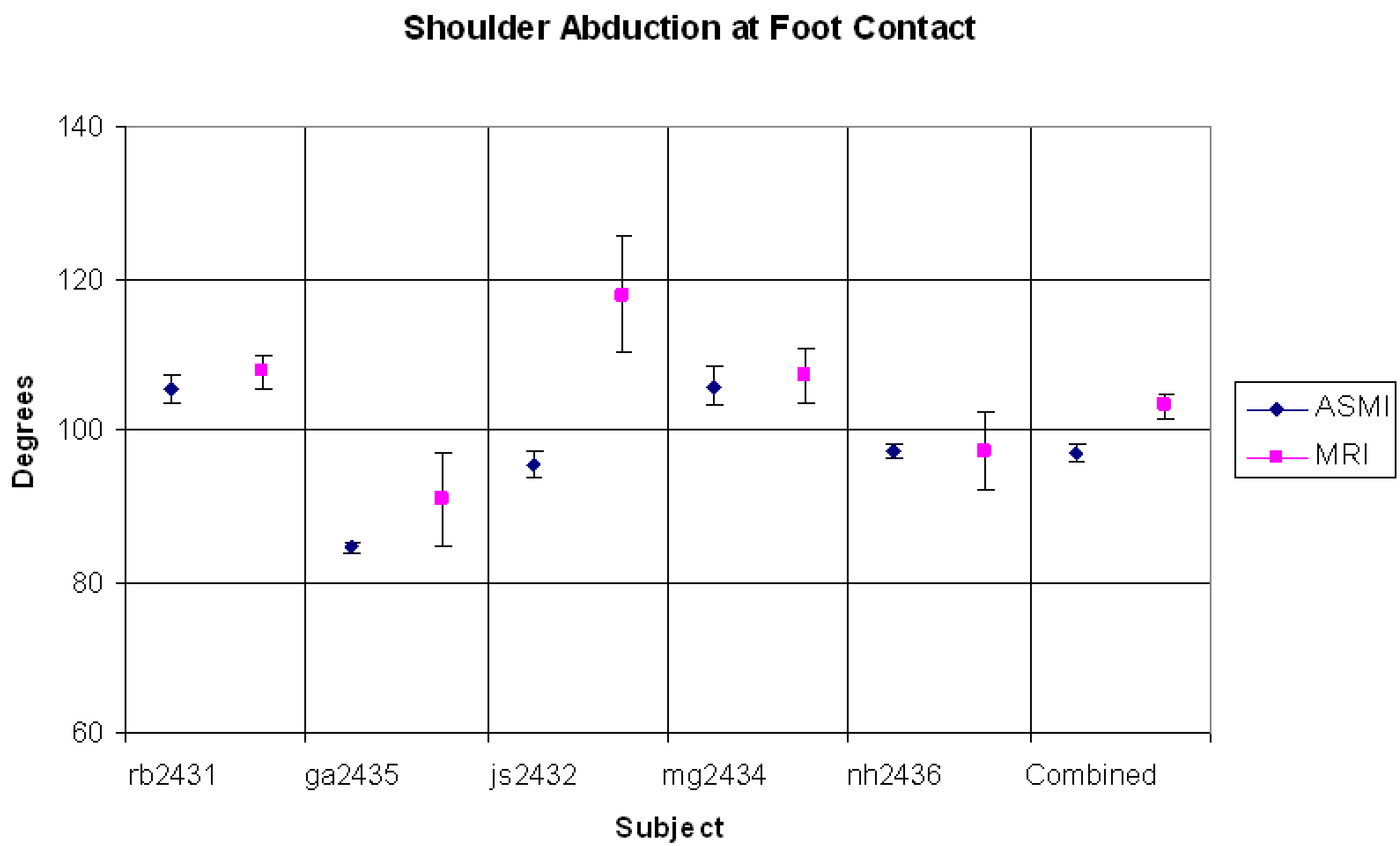
	js2432			mg2434	
Kinematic Parameter	ASMI	MRI		ASMI	MRI
	(n = 8)			(n = 9)	
Foot Contact					
Shoulder Abduction	95.45 ± 1.87	117.83 ± 7.66		105.85 ± 2.58	107.28 ± 3.63
Shoulder Horizontal Adduction	-33.30 ± 0.68	-36.94 ± 12.98		-7.73 ± 4.15	-8.57 ± 4.07
Shoulder External Rotation	23.87 ± 8.06	2.87 ± 20.39		78.11 ± 14.18	71.60 ± 5.06
Knee Flexion	55.50 ± 3.28	64.93 ± 3.17		44.38 ± 3.71	45.43 ± 4.93
Elbow Flexion	91.93 ± 3.11	90.16 ± 5.43		81.34 ± 5.17	73.81 ± 6.23
Maximum Shoulder Horizontal Adduction	7.37 ± 0.53	9.74 ± 12.44		29.84 ± 0.90	12.53 ± 1.15
Maximum Shoulder External Rotation	177.10 ± 1.21	166.44 ± 11.24		169.82 ± 1.96	185.54 ± 2.60
Ball Release					
Trunk Flexion	33.16 ± 1.03	31.99 ± 1.25		26.12 ± 2.00	24.78 ± 2.09
Elbow Flexion	12.89 ± 0.55	15.40 ± 10.24		20.62 ± 1.30	7.25 ± 2.09
Shoulder Horizontal Adduction	-2.13 ± 0.84	-13.69 ± 6.96		22.26 ± 1.12	3.20 ± 1.98
Maximum Elbow Flexion	12.87 ± 0.54	14.76 ± 10.90		16.97 ± 1.05	2.05 ± 0.51
Ball Velocity (m/s)	37.05 ± 0.37			33.93 ± 0.61	

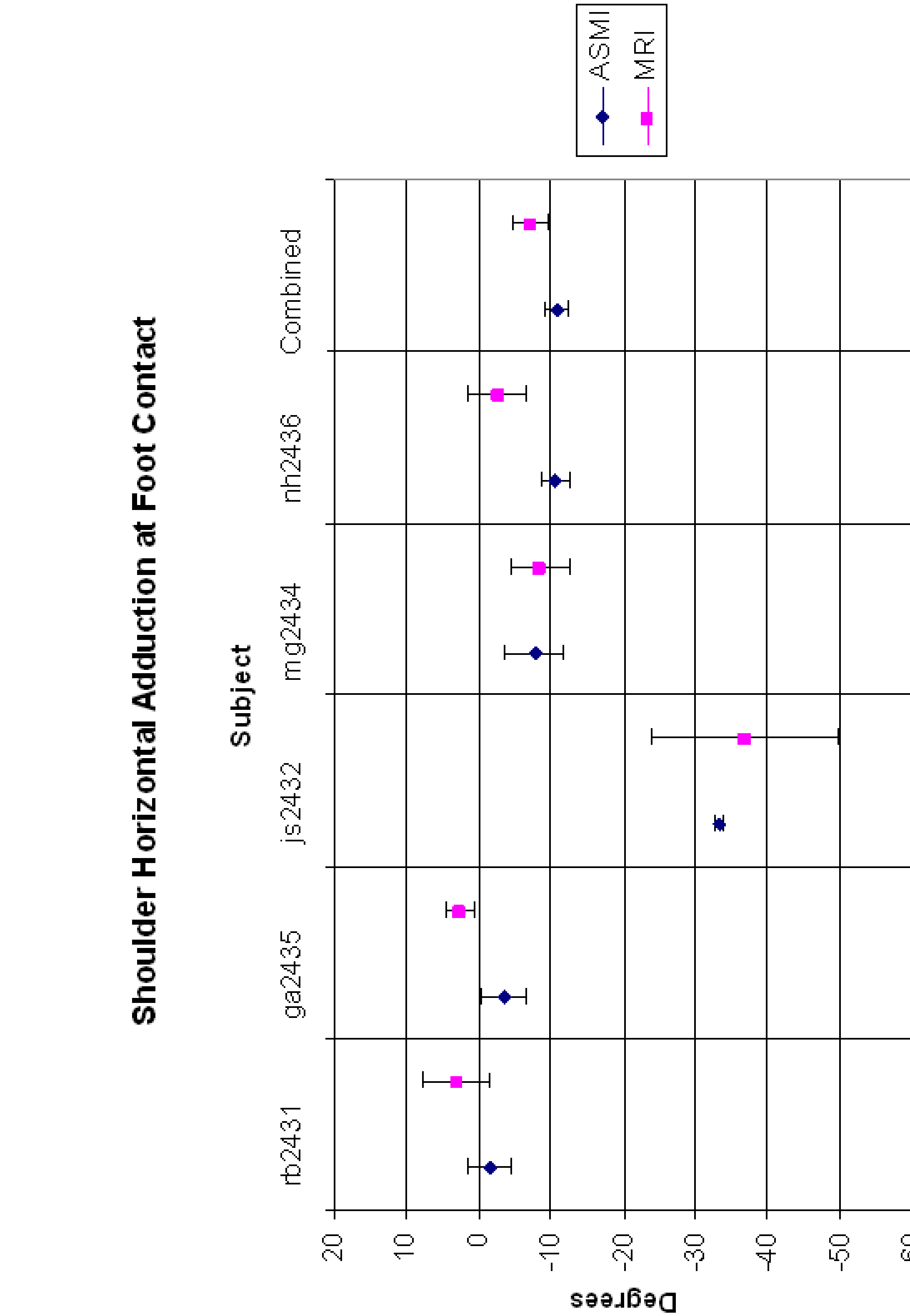
	nh2436	
Kinematic Parameter	**ASMI**	**MRI**
	(n = 10)	
Foot Contact		
Shoulder Abduction	97.34 ± 0.98	97.25 ± 5.20
Shoulder Horizontal Adduction	-10.64 ± 1.96	-2.71 ± 4.08
Shoulder External Rotation	41.22 ± 8.05	44.96 ± 16.83
Knee Flexion	41.34 ± 3.13	39.56 ± 3.05
Elbow Flexion	77.29 ± 4.47	63.59 ± 7.97
Maximum Shoulder Horizontal Adduction	9.86 ± 1.16	39.29 ± 2.77
Maximum Shoulder External Rotation	179.83 ± 1.40	184.91 ± 17.52
Ball Release		
Trunk Flexion	34.32 ± 1.56	30.91 ± 1.87
Elbow Flexion	23.44 ± 1.57	9.81 ± 5.52
Shoulder Horizontal Adduction	2.51 ± 0.75	-4.10 ± 1.80
Maximum Elbow Flexion	20.70 ± 0.62	4.66 ± 0.74
Ball Velocity (m/s)	34.42 ± 0.59	

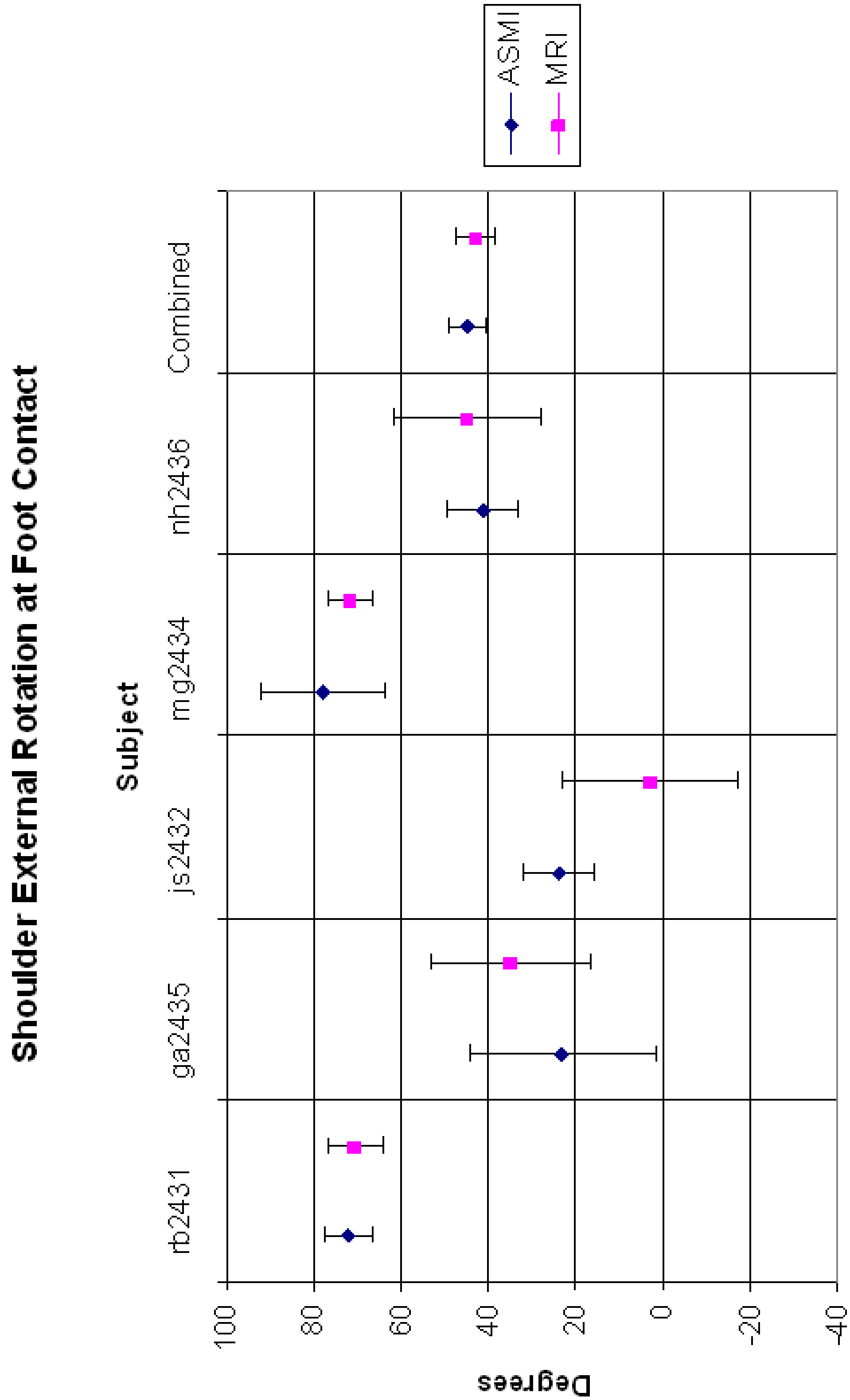
APPENDIX F

AVERAGE RESULTS FOR KINEMATIC PARAMETERS AT FOOT CONTACT

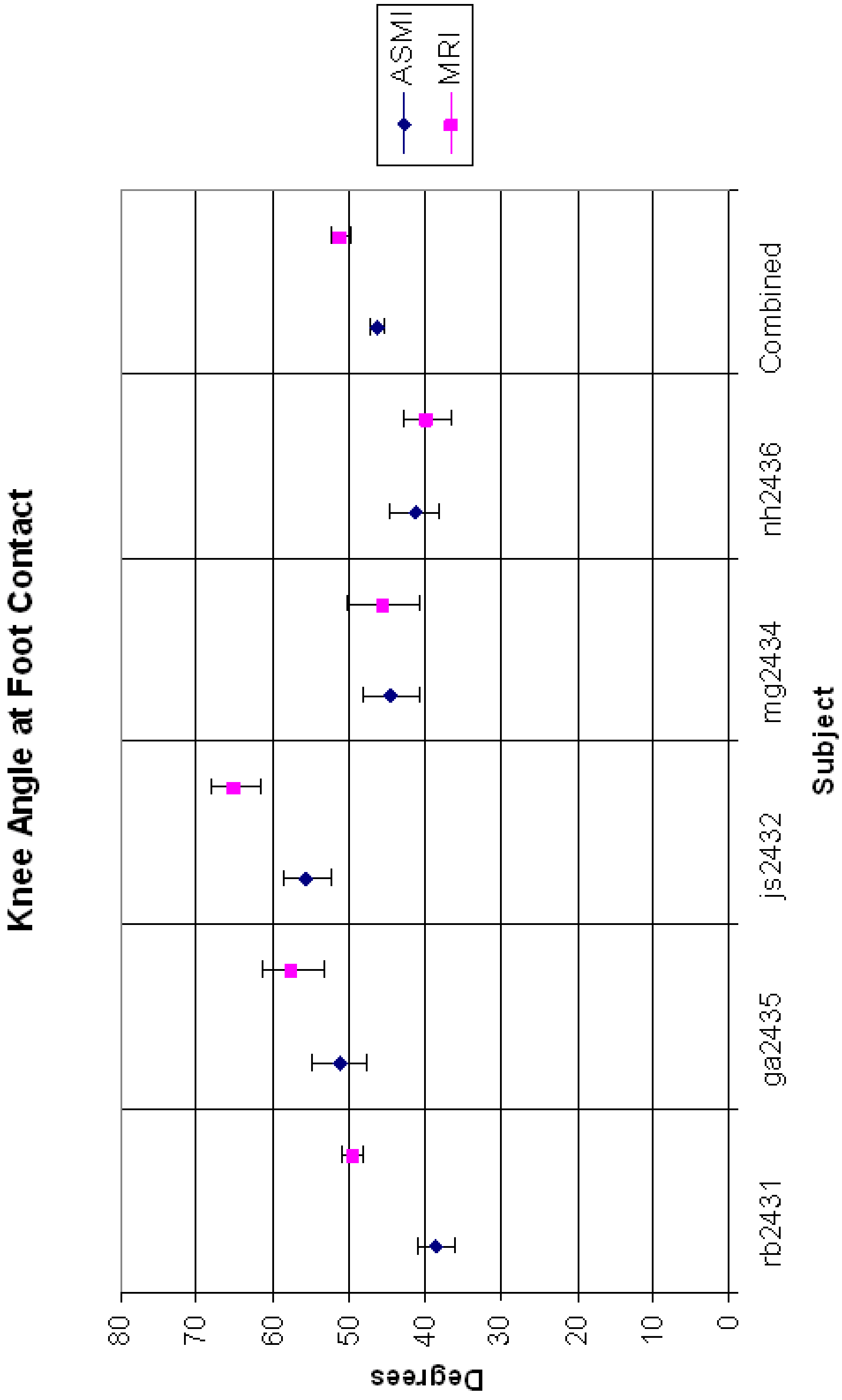
This appendix includes charts for the data collected for all of the kinematic parameters looked at during the foot contact phase of the pitching motion. The parameters include shoulder abduction, shoulder horizontal adduction, shoulder external rotation, knee flexion, and elbow flexion. The charts represent the mean angle values calculated for each subject along with their individual standard deviations. For the combined data, a standard error of the mean is represented.


Shoulder Abduction at Foot Contact
140
120
100
80
60
Degrees
rb2431
ga2435
js2432
mg2434
nh2436
Combined
Subject
ASMI
MRI

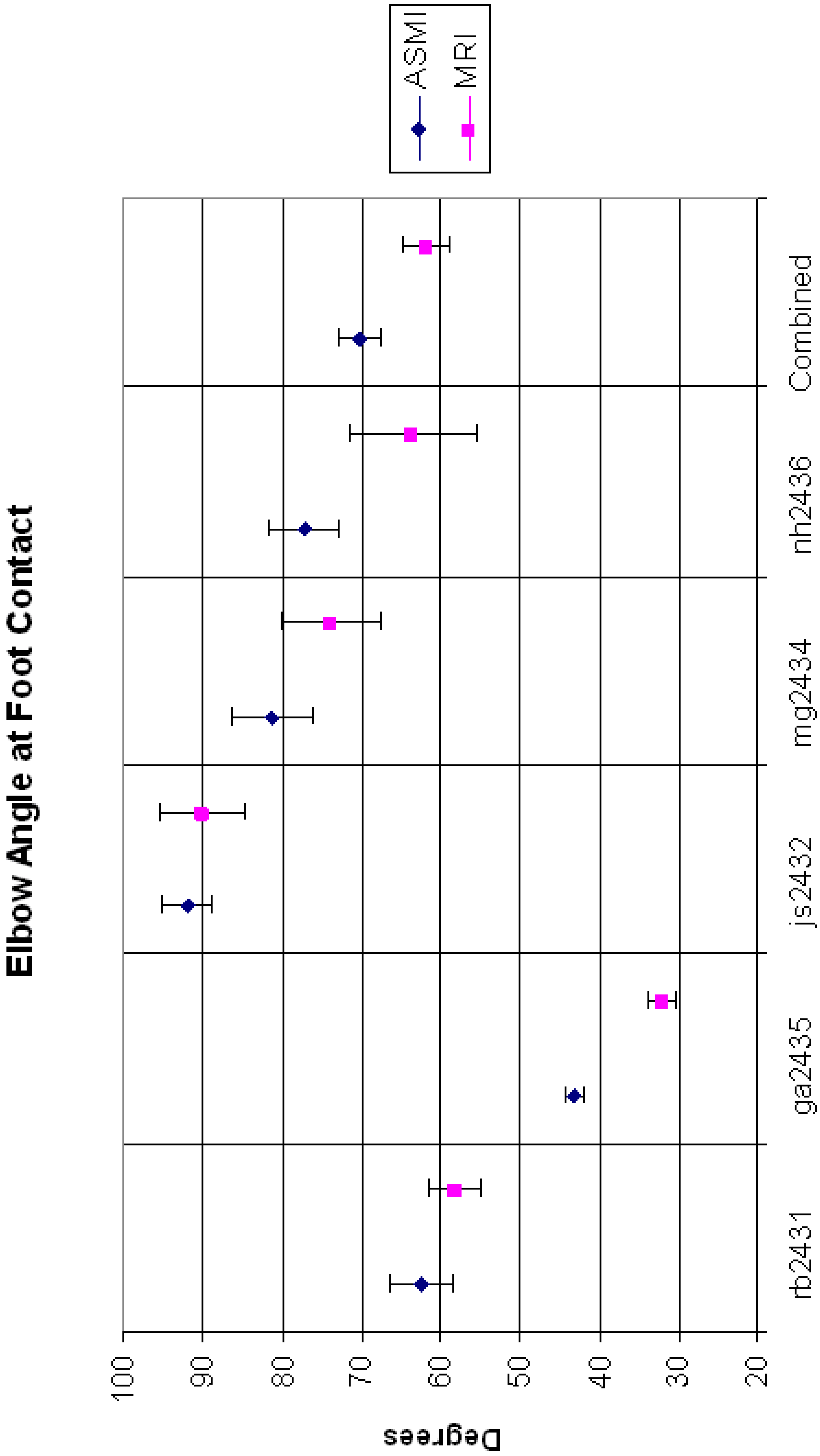

Shoulder Horizontal Adduction at Foot Contact
Subject
Degrees
20
10
0
-10
-20
-30
-40
-50
-60
rb2431
ga2435
js2432
mg2434
nh2436
Combined
ASMI
MRI



Shoulder External Rotation at Foot Contact
Subject
Degrees
100
80
60
40
20
0
-20
-40
rb2431
ga2435
js2432
mg2434
nh2436
Combined
ASMI
MRI



Knee Angle at Foot Contact
Degrees
80
70
60
50
40
30
20
10
0
rb2431
ga2435
js2432
mg2434
nh2436
Combined
Subject
ASMI
MRI

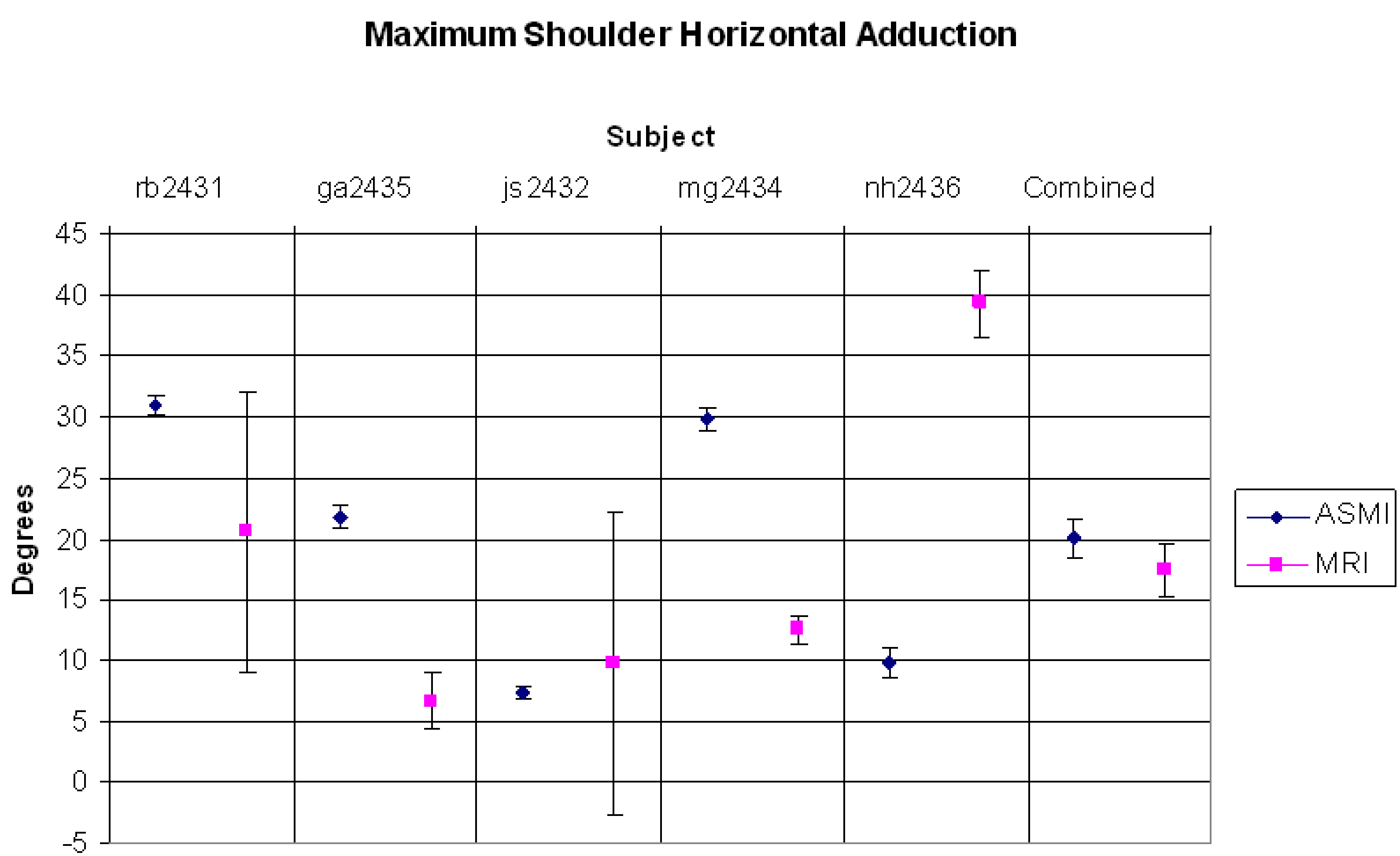


Elbow Angle at Foot Contact
ASMI
MRI
Degrees
100
90
80
70
60
50
40
30
20
rb2431
ga2435
js2432
mg2434
nh2436
Combined
Subject

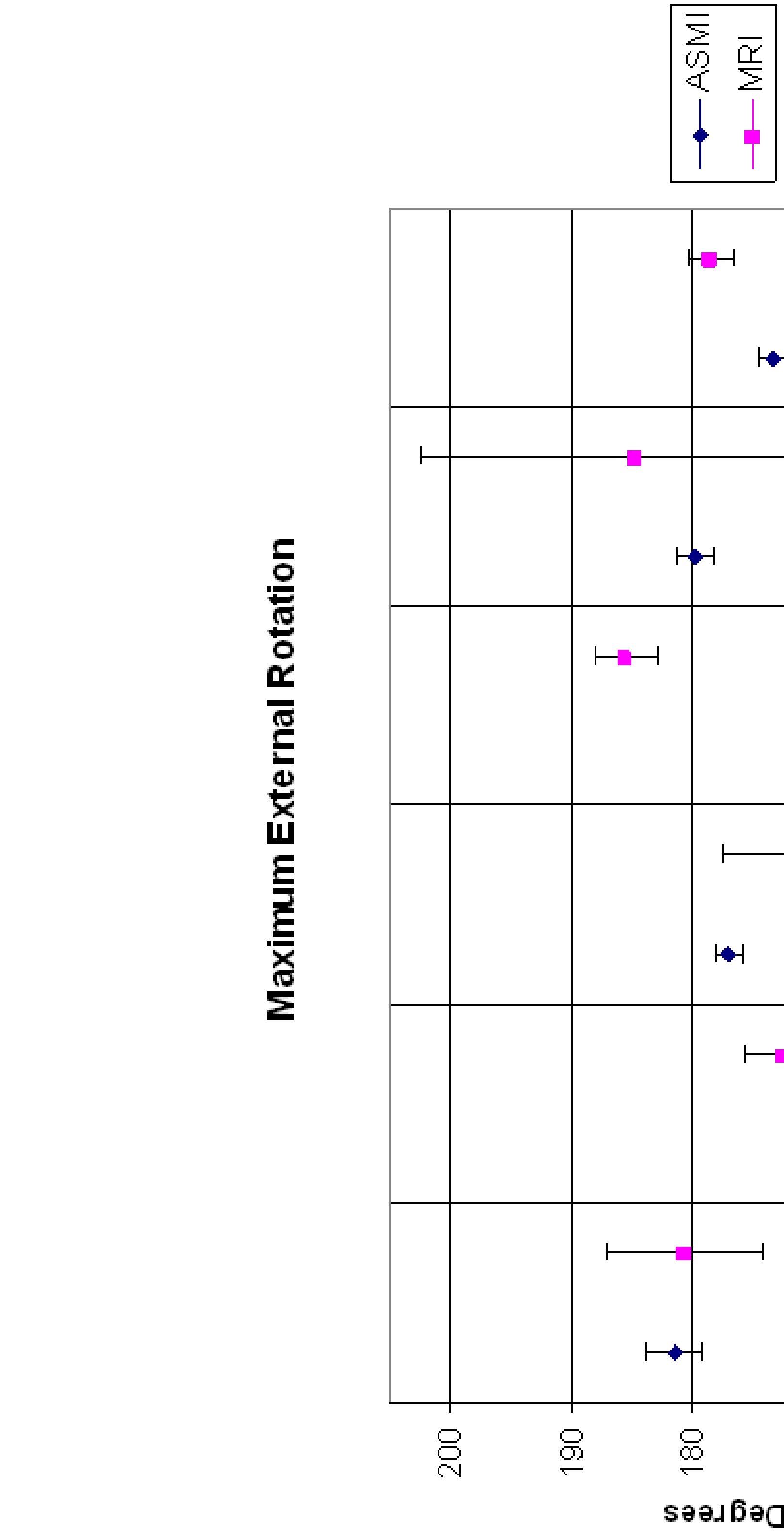
APPENDIX G

AVERAGE RESULTS FOR KINEMATIC PARAMETERS AT MAXIMUM VALUE

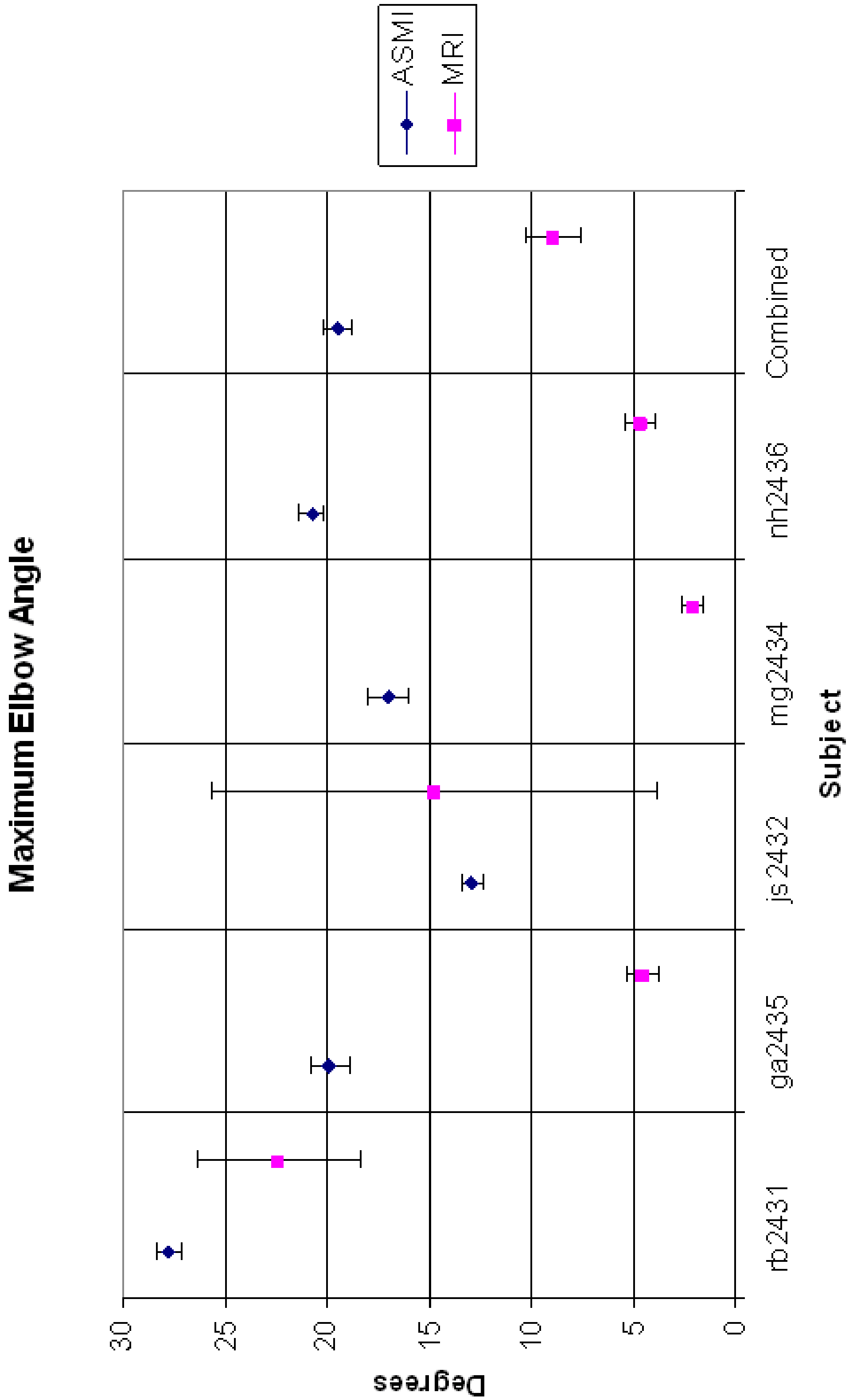
This appendix includes charts for the data collected for all of the kinematic parameters looked at, at their respective maximum value during the course of the pitching motion. The parameters include shoulder horizontal adduction, shoulder external rotation, and elbow flexion. The charts represent the mean angle values calculated for each subject along with their individual standard deviations. For the combined data, a standard error of the mean is represented.



Maximum Shoulder Horizontal Adduction
Subject
rb2431
ga2435
js2432
mg2434
nh2436
Combined
Degrees
45
40
35
30
25
20
15
10
5
0
-5
ASMI
MRI



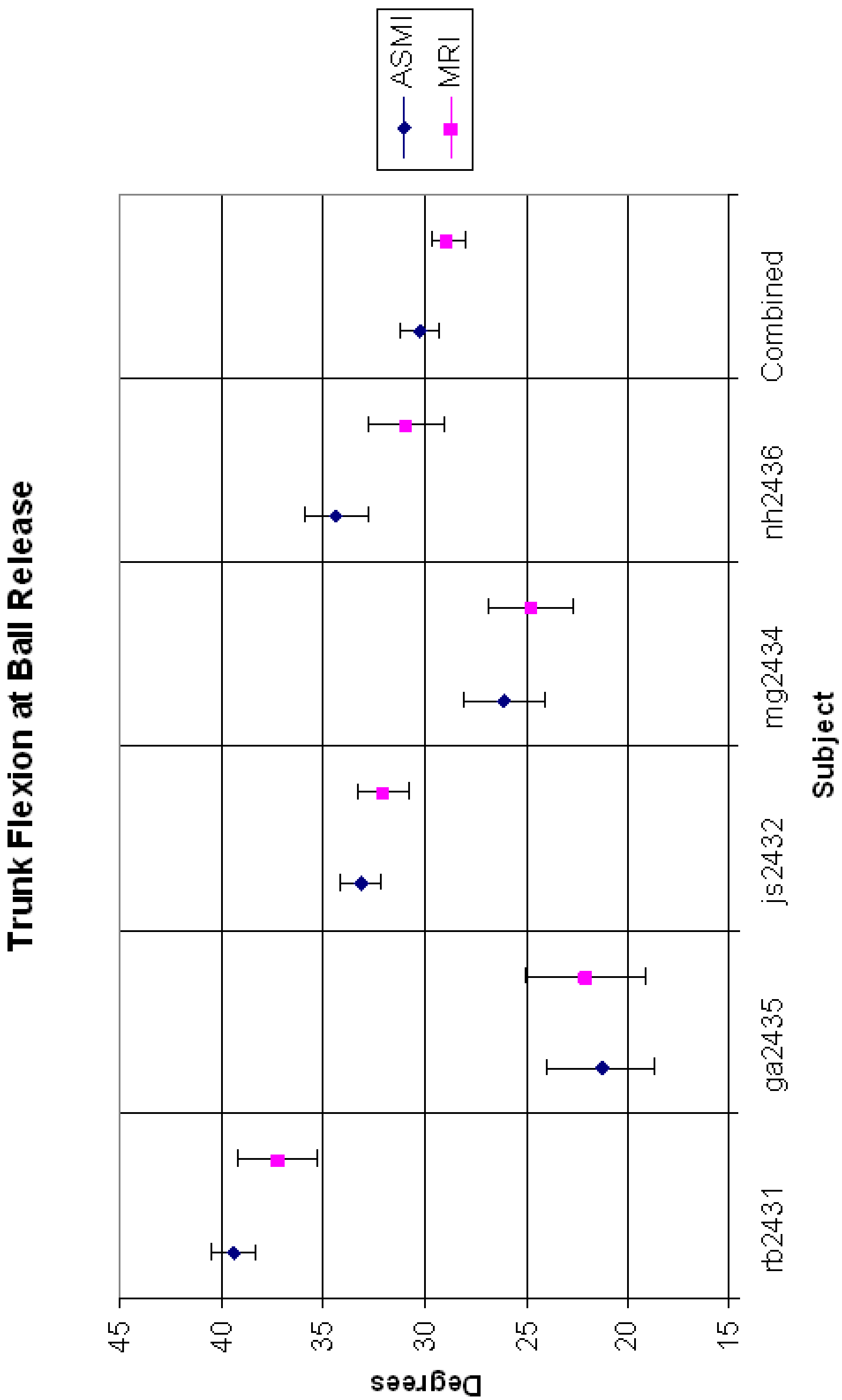
Maximum External Rotation
Degrees
200
190
180
170
160
150
rb2431
ga2435
js2432
mg2434
nh2436
Combined
Subject
ASMI
MRI

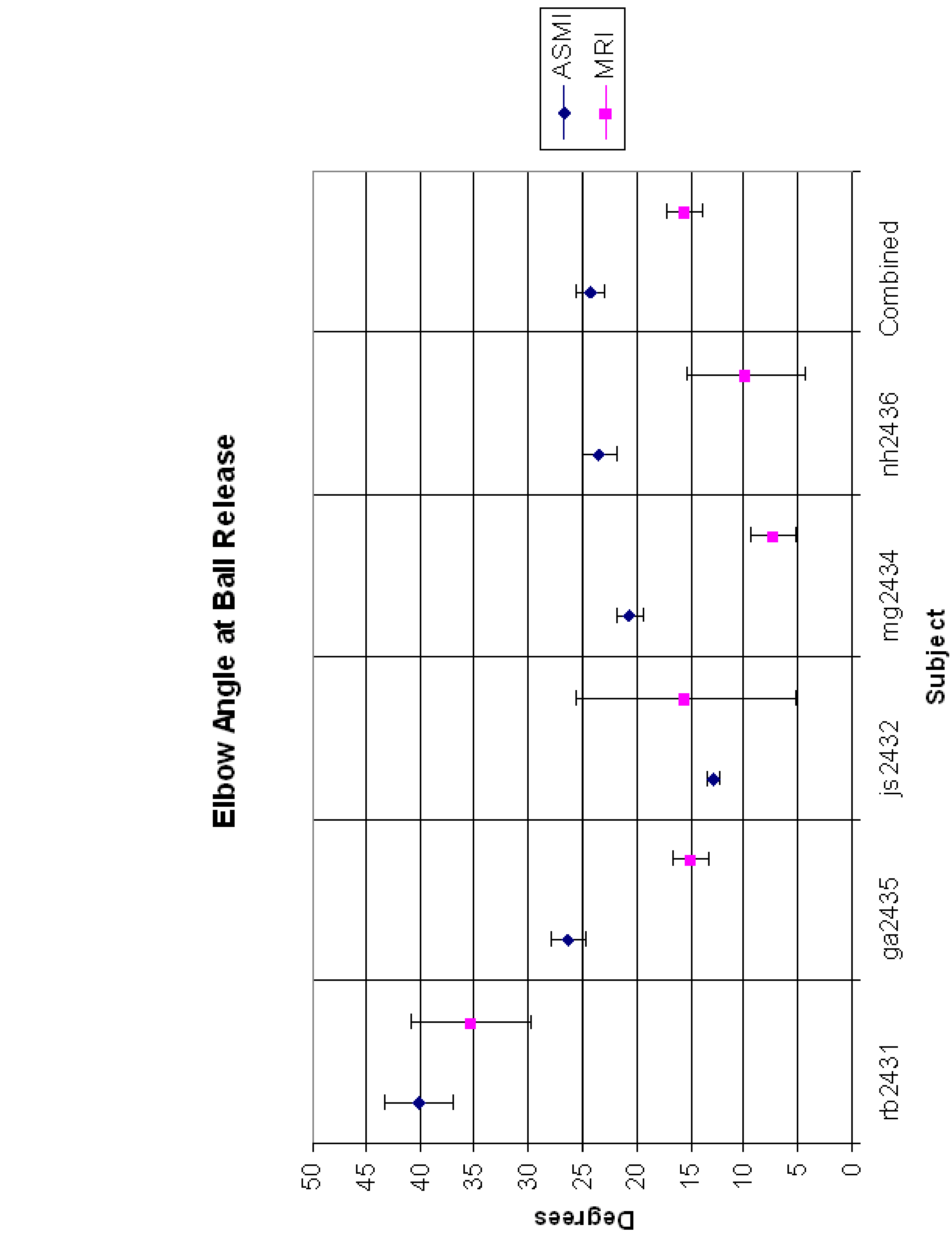

Maximum Elbow Angle
Degrees
30
25
20
15
10
5
0
rb2431
ga2435
js2432
mg2434
nh2436
Combined
Subject
ASMI
MRI

APPENDIX H

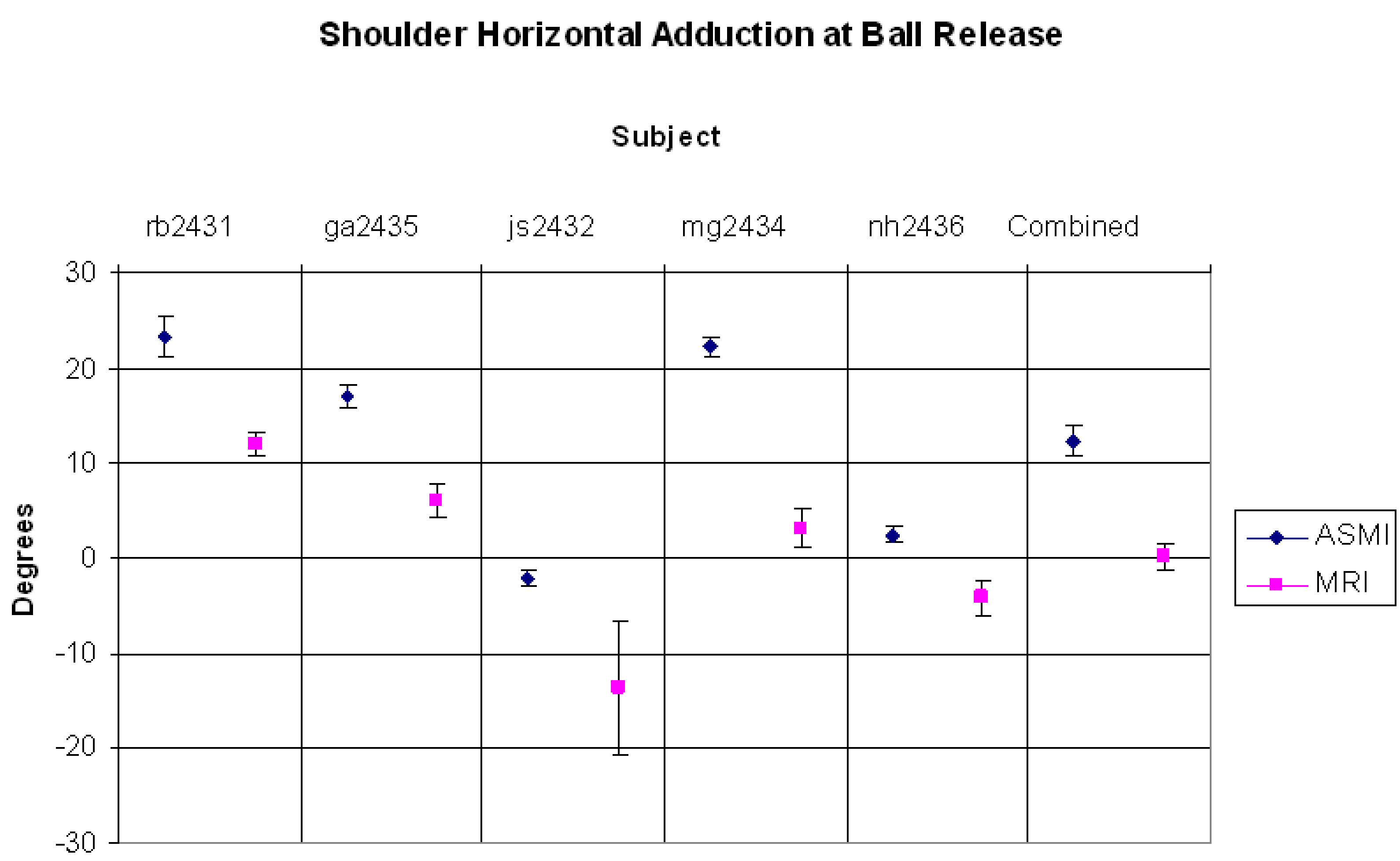
AVERAGE RESULTS FOR KINEMATIC PARAMETERS AT BALL RELEASE

This appendix includes charts for the data collected for all of the kinematic parameters looked at during the ball release phase of the pitching motion. The parameters include trunk flexion, elbow flexion, shoulder horizontal adduction. The charts represent the mean angle values calculated for each subject along with their individual standard deviations. For the combined data, a standard error of the mean is represented.


Trunk Flexion at Ball Release
Degrees
45
40
35
30
25
20
15
rb2431
ga2435
js2432
mg2434
nh2436
Combined
Subject
ASMI
MRI



Elbow Angle at Ball Release
Degrees
50
45
40
35
30
25
20
15
10
5
0
rb2431
ga2435
js2432
mg2434
nh2436
Combined
Subject
ASMI
MRI


Shoulder Horizontal Adduction at Ball Release
Subject
rb2431
ga2435
js2432
mg2434
nh2436
Combined
Degrees
30
20
10
0
-10
-20
-30
ASMI
MRI