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Biomechanics of the lower extremity during a windmill style fast-pitch

Traci Lee Haydu

To the Graduate Council:

I am submitting herewith a thesis written by Traci Lee Haydu entitled "Biomechanics of the lower extremity during a windmill style fast-pitch." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Human Performance and Sport Studies.

Songning Zhang, Major Professor

We have read this thesis and recommend its acceptance:

Wendell Liemohn, Craig A. Wrisberg

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew

Associate Vice Chancellor and
Dean of The Graduate School

BIOMECHANICS OF THE LOWER EXTREMITY DURING A WINDMILL STYLE FAST-PITCH

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Traci L. Haydu
May 1999

DEDICATION

This thesis is dedicated to my parents,

Steven and Kathryn Haydu, who have always

encouraged and supported me, and deserve

endless appreciation.

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I would like to thank my major professor, Dr. Songning Zhang for his guidance and encouragement throughout my graduate studies. He has undoubtedly brought more out of me than I ever believed would be possible. I would also like to express my sincere appreciation to my other committee members, Dr. Wendell Liemohn, and Dr. Craig Wrisberg for their assistance and suggestions. I am grateful and honored to have learned from and worked with such exceptional faculty and staff as those in the Exercise Science Unit. Their dedication and commitment to education and the students have truly made my time at the University of Tennessee rewarding and memorable.

ABSTRACT

The windmill style fastpitch involves an array of motor skills requiring sequential coordination of the upper and lower extremities. Characteristic of the motion is a powerful drive and rapid transfer of force on to the striding lower extremity. This may result in a substantial breaking force over a short period of time. The purpose of this study was to determine the kinematic responses and magnitude of ground reaction forces (GRF) created by the stride leg in selected windmill pitches. Five female intercollegiate fastpitch softball pitchers (age: 22.6 yrs, body mass: 69.0 kg) performed 5 pitches of the fastball (FB), change-up (CH), dropball (DB), curveball (CB) and riseball (RB). Simultaneous recordings of video (60hz) and GRF (1000 hz) were obtained and synchronized for each trial. Kinematic variables evaluated included stride length, ball velocity, joint angle at contact (JAC), maximum angle (MAX), time to maximum angle (TMAX), minimum angle (MIN) and time to minimum angle (TMIN). Primary kinetic variables evaluated were first peak force (F1), second peak force (F2) and maximum brake force (F_b). Single factor ANOVAs revealed significant kinematic differences ($p < 0.05$) between pitches for MAX and MIN for hip, knee and ankle, as well as, differences in JAC for hip and knee.

Stride lengths of the participants in this study indicate that different strategies were used in the delivery of the various pitches. Stride lengths were longest for the riseball and shortest for the change-up. In general, the pitchers

adopted a style characterized by extended hip and knee joint and plantarflexed ankle joint.

Comparison of stride lengths to total body range of motion at contact indicated that longer stride lengths are associated with a less upright position of the body. In general the fastball, curveball and riseball had longer stride lengths and greater total body range of motion. In contrast, the body assumes a more upright position in pitches with a shorter stride length, such as the change-up and dropball. The results also indicated trends of slower ball velocities with a more upright body position.

Peak vertical forces during pitching are higher than those reported in walking and low impact aerobics. In addition, peak vertical forces experienced during pitching appear to be similar to those reported in distance running and high impact aerobics. However, peak forces are lower than those reported in jump/landing skills in basketball and volleyball.

Maximum braking forces of pitching are higher than those reported in running and walking. In addition, the braking forces produced in pitching are higher than common movements performed in basketball, with the exception of landing after a layup shot. The riseball had the highest braking force followed by the fastball, whereas the lowest braking force occured in the change-up. The findings indicate a trend that pitches with the highest F1 values are accompanied by high maximum braking forces and vice versa for pitchers with the lowest F1 values. These findings indicate trends that the pitches with the highest F1 values are accompanied by high maximum braking forces and vice versa for pitchers with the lowest F1 values.

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CHAPTER I

INTRODUCTION

Fastpitch softball has become increasingly popular across the United States over the past several years. In 1994, it was estimated that over 40 million people were participating in the sport of softball (Donovan & Toronto, 1994). The recent success and media attention of the USA Olympic Softball team in Atlanta in 1996, and the addition of softball programs at the collegiate level, as a result of Title IX, has increased the number of females participating in fastpitch softball. Furthermore, professional softball leagues are beginning to evolve in regions of the United States.

Despite the growth in the sport of fastpitch softball, the biomechanics of the sport has received very little attention in the literature. In the past 25 years, there have been a limited number of investigators that have performed a kinematic analysis of the windmill pitch (Zollinger, 1973; Alexander & Haddow, 1982; Wilson, McDonald & Neal, 1985; Greene, Tant, McKeon, 1994 and Werner, Murray, Levy, Smith, Plancher & Hawkins, in press). The main focus has been on the general overarm throwing motion in baseball and softball (Atwater, 1979; Dillman, Fleiseg, & Andrews, 1993; Fleiseg, Barrentine, Escamilla & Andrews, 1996). In addition, there are a few studies published pertaining to batting mechanics in fastpitch softball (Messier & Owen, 1985; Messier & Owen, 1986).

The study of the windmill pitch is still in its infancy. Recently, there has been one published study examining the electromyographic activity of the shoulder muscles during a windmill fastpitch (Maffet, Jobe, Pink, Brault, & Mathiyakom, 1997). They identified the muscle firing patterns in the shoulder girdle muscles during different phases of the windmill pitch. Two of the most recent studies have documented the biomechanical differences between the windmill pitch and the baseball pitch (Maffet et al., 1997; Werner et al., in press). However, the biomechanics of the lower extremity in the windmill pitch has been neglected in the literature. Much of the orthopedic literature regarding overarm athletes, centers on the upper extremity, specifically the shoulder complex. Results from these studies have led to advances in the diagnosis, treatment, and prevention of shoulder injuries. Training and conditioning techniques have also improved, thereby enhancing athletic performance.

Force production is generated from the use of the legs and trunk in both the overarm throw and the windmill pitch. In the windmill pitch, weight shift is important for balance, coordination and force production (Werner, 1994). Weight shift occurs as the result of striding out and rotating the hips to an "open" position (a right-handed pitcher would be facing third base) then rotating back to a "close" position as the arm swings through and releases the ball. As the pitcher strides toward home plate, the lead foot contacts the ground. The ground reacts by providing resistance and a reaction equal and opposite to the force altered by foot contact (Werner, 1994). The ground reaction forces (GRF) travel proximally through the segments of the lower extremity (Werner, 1995). The coordinated movements of the hips and trunk are the link between the upper and lower extremities in the windmill pitch.

A combination of the lower extremity, trunk, and circular movement of the arm, in addition to a forceful forward transfer of the pitcher's center of mass, contributes to the velocity of a pitch (Olson & Hunter, 1987; Werner, 1994). The coordinated sequence of knee and hip extension, plantar flexion of the push leg, and the stride action of the leading leg causes the pelvis and center of mass to move towards home plate (Olson & Hunter, 1987). As the leading foot contacts the ground, forward momentum is created by the throwing arm and push leg. The momentum is absorbed in a brief period of eccentric contraction of the quadriceps muscles in the stride leg (Olson & Hunter, 1987).

GRF measure the intensity and duration of stress the body is subjected to during contact with the ground. GRF has been examined in normal functional activities such as walking, running, jumping and landing (Elftman, 1939; Hamill, Bates & Knutzen, 1984; Cavanagh & LaFortune, 1980; Munro, Miller & Fugelvand, 1987; Dufek & Bates, 1990; Devita & Skelly, 1992; Ricard & Veatch, 1990; Michaud, Rodriguez-Zayas, Armstrong & Hartnig, 1993).

GRF has also been investigated specific skills in the sports of volleyball, basketball, tennis, fencing, and baseball (Adrian & Laughlin, 1983; McClay, Robinson, Andriacchi, Frederick, Gross, Martin, Valiant, Williams & Cavanagh, 1994; Van Gheluwe & Hebblelinck, 1996; Millbank & Nicol, 1990; Fink, 1993; MacWilliams, Choi, Perezous, Chao & MaFarland, 1998). The lack of documentation of GRF in windmill pitching warrants further study. Therefore, the purpose of this study was to determine the kinematic responses and magnitude of GRF created by the stride leg in selected windmill pitches.

Information about pitching biomechanics may assist coaches in optimal technique instruction, assist athletic trainers in prevention and treatment of pitching related injuries, and assist strength coaches in conditioning athletes using sport specific loads and motions. Such knowledge may provide insight into possible mechanisms of injury, and tissues susceptible to injury. Furthermore, injury prevention through conditioning and training, may also be enhanced.

Delimitations of the Study

The study was conducted within the following delimitations:

1. Five healthy female windmill softball pitchers between the ages of 18 and 35 years of age participated in the study.

2. Participants had at least 10 years of pitching experience.
3. All participants were right-handed pitchers.
4. The pitchers had participated in fastpitch softball at the intercollegiate level.
5. All participants were free from injury and moderately active at the time of testing.
6. Pitches executed were the fastball, dropball, change-up, curveball and riseball.
7. Kinematic and kinetic data for each pitch from delivery to follow-through were analyzed for each trial.
8. Data collection for each participant was completed in one session.

Limitations of the Study

The study was limited as follows:

1. The participants were not randomly selected, but recruited based on their pitching experience at the intercollegiate level.
2. Three of the five pitchers did not throw a curveball.
3. Errors of force platform and video systems are always present but were considered acceptable within the specifications of the manufacturers.

CHAPTER II

REVIEW OF LITERATURE

Windmill Pitch Technique

The windmill softball pitch is the most common pitching motion used in fastpitch softball. The windmill motion allows for more efficient speed and accuracy; however, technically it is the most difficult pitching technique because it utilizes the greatest range of motion (Wilson, McDonald & Neal, 1985).

Maximal arm angular speed has been reported to be equivalent to six revolutions per second in eight elite female pitchers (Werner, 1995). To achieve maximal pitch velocity, the softball should be released parallel to the thigh and perpendicular to the ground (Greene, Tant & McKeon, 1994). The velocity of the ball is developed in a short period of time through a precise sequence of movements, which result in the forward transfer of the pitcher's center of gravity (Olson & Hunter, 1987).

The susceptibility for error becomes more likely as increases occur in shoulder velocity and range of motion. Coordination and rhythm of the pitch are disrupted as a result of any deviations in the speed or the circular path of the arm during the motion. The disruption of the coordination and rhythm during the execution of the pitch results in decreased force production and accuracy (Werner, 1994).

The windmill pitch is a series of coordinated movements of the upper and lower portions of the body. The sequence of the pitch has been divided into as few as two phases (Wilson, McDonald, & Neal, 1985) and as many as six different phases (Maffet, Jobe, Pink, Brault, & Mathiyakom, 1997); however, it is typically described in four generic phases: wind-up, delivery, ball release, and follow-through (Rutherford, 1985; Hunter & Olson, 1987). The pitching motion occurs rapidly; therefore sequencing the phases in the correct order is very difficult.

The pitcher begins by taking the position on the pitching rubber. The hands are usually held in front of the body at waist level with the ball inside of the glove. The feet are approximately at a shoulder width apart with the foot of the throwing side (pivot leg) contacting the front of the pitching rubber and the opposite foot (stride leg) contacting the rear of the pitching rubber. The initial stance phase may vary somewhat between pitchers, with typically minimal deviations. In general, the stance should allow for equal distribution of the pitcher's body weight.

A combination of the leg, hip, trunk, and circular movement of the arm, in addition to a forceful forward transfer of a pitcher's center of mass, contributes to the velocity of a pitch. The coordinated sequence of knee and hip extension and plantar flexion of the push leg, in conjunction with the stride action of the leading leg, causes the pelvis and center of mass to move towards home plate (Olson & Hunter, 1987). As the leading foot contacts the ground, forward momentum is created by the throwing arm and push leg. The momentum is absorbed in a brief period of time through the eccentric contraction of the quadriceps muscles of the stride leg (Olson & Hunter, 1987).

Windup Phase

The windup phase consists of a series of movements used to overcome static inertia and begin the forward movement of the body. There is wide variation among pitchers in the windup phase of the pitch, such as the amount of hyperextension of the arm, trunk flexion and elbow position (Maffet et al., 1997). However, all pitchers complete this phase with the arm extended and moving forward towards home plate.

One windup technique utilizes hip and upper trunk, where shoulders remain parallel to the pitching rubber (Olson & Hunter, 1987). Another, more common, technique involves posterior shoulder extension of the pitching arm just prior to shoulder flexion. Maffet and colleagues (1997) observed a windup range from 0 to 90° of arm hyperextension in a group of ten collegiate level pitchers. This windup technique is believed to allow for greater force production (Olson & Hunter, 1987) due to the stretch reflex mechanism (Alexander & Haddow, 1982). When the concentric contraction of the shoulder joint is preceded by a rapid and forceful eccentric contraction, greater concentric force is produced (Komi, 1984). The primary purpose of the windup is to initiate forward movement of the body. Furthermore, it allows for greater angular velocity to be developed at the shoulder (Rutherford, 1985; Olson & Hunter, 1987).

Delivery of the Pitch

The delivery of the pitch can be divided into ascent and descent of the arm. During the ascent, the pitching arm is internally rotated as it reaches 90° of flexion. It is further elevated to 180° of flexion and is externally rotated as it reaches a position overhead (Maffet et al., 1997). The arm remains externally rotated, traveling downward with the wrist hyper-extended, during the descent phase, until the ball is released.

The hands begin to move together, down and forward, to knee height in the beginning of the ascent phase of the arm (Wilson, McDonald & Neal, 1985; Rutherford, 1985; Olson & Hunter, 1987). This motion causes the shoulders to move forward towards home plate. The pitching arm begins to ascend until it reaches a point overhead (12 o'clock position) then it begins to rotate laterally. Slight knee and trunk flexion initiates the forward transfer of the pitcher's center of gravity (Wilson, McDonald & Neal, 1985). There is a forceful downward push with the pivot foot with hip flexion and knee extension of the stride leg, as it moves forward in a flexed position (Rutherford, 1986; Wilson, McDonald & Neal, 1985). Both arms continue in a forward and upward motion as the legs propel the body towards home plate. As the arms reach shoulder level, the non-throwing arm stops and assists in balance by counteracting the circular motion of the throwing arm (Werner, 1994; Rutherford, 1985; Wilson, McDonald & Neal, 1985). In addition, the non-throwing side transfers its momentum to the pitching side. The dominant arm continues upward to a 12 o'clock position which marks the end of the ascent phase. During this time, the body weight keeps shifting forward and the body begins to rotate to an "open" position.

The downward acceleration of the throwing arm, from the 12 o'clock to 3 o'clock position, marks the onset of the descent or "power" phase of the delivery. During this time the body remains rotated towards the pitching arm. The stride leg contacts the ground as the pitching arm reaches the 9 o'clock position, and absorbs the momentum that is created by the previous actions of the ipsilateral arm and leg (Olson & Hunter, 1987). As it approaches the 12 o'clock position, the throwing arm should be close to the body when the foot contacts the ground. Werner et al. (in press) found an increase in distraction force at the shoulder when the pitching arm deviated from the correct position. The weight of the body lands on the stride leg and the hip and trunk of the pitcher rotate toward home plate. The rotation of the body into the "closed' position transfers more power to the arm just before ball release (Maffet et al., 1997). The back leg pushes the throwing side forward, which increases the loading on the stride leg. The stride leg is planted firmly to allow the leg to "pull" equally as hard backward against the ground in order to rotate the hips to the "closed" position (Werner, 1994). The non-throwing arm is then pulled backwards to assist the stride leg in hip rotation. The rotation of the hips facilitates the forward movement of the throwing shoulder, resulting in a segmental whip-like action of the arm for an effective ball release.

An important element of the delivery phase of the windmill pitch is weight shift. Proper weight shift is crucial to the coordination and rhythm of the pitch which are beneficial to force production (Werner, 1994). A substantial amount of force production is generated from the use of the legs and trunk in the windmill pitch (Werner, 1994). The transfer of energy from the legs to the upper extremity can only occur with proper weight shift. Weight shift is a result of hip rotation from an "open" to "closed" position, allowing the arm to swing through and release the ball.

Proper hip rotation and weight shift also reduces the stress on the throwing arm and is important for ball velocity (Werner, 1994). Werner and colleagues (in press) found that the distraction force at the shoulder ranged between 0.5 and 1.5 times body weight (BW). This force is similar to that found in baseball pitchers at the point of release. Proper pitching mechanics such as trunk rotation, positioning of the pitching arm when the foot contacts the ground and at the time of ball release, as well as stride length and position, can decrease distraction force at the shoulder (Werner et al., in press).

Ball Release

The ball release represents the termination of the delivery phase. As previously stated, hip rotation to a closed position allows the transfer of momentum from the legs to the throwing arm (Olson & Hunter, 1987). The type of pitch may influence the release of the ball, but generally, the ball is released parallel to the thigh and perpendicular to the ground with a powerful wrist snap. The position of the throwing arm at ball release, elbow slightly flexed, is important for reducing stress on the shoulder (Werner et al., in press).

Accuracy of the pitch and ball speed is dependent upon the proper sequencing of the upper and lower extremities. Werner et al., (in press) determined specific parameters related to ball speed. The throwing arm should be close to the body (in the same plane) and near the top of the backswing when the stride foot contacts the ground. The stride leg should be flexed approximately 30° at the knee upon contact with the surface, with the foot internally rotated at a 10° to 30° angle. Arm speed at the time of release is also important. The velocity of the arm's proximal segments should decrease in order to increase the velocity at the distal end of the arm (Alexander & Haddow, 1982). Therefore, the speed of the hand should be at maximal velocity for increased ball speed.

Follow-Through

The follow-through occurs after the release of the ball. It serves to decelerate the speed of the various body parts to dissipate the forces that are generated during the delivery of the ball. Deceleration reduces the potential for injury to musculature and connective tissues of the arm. This phase has been described as a series of eccentric contractions of the shoulder and elbow extensors, forearm supinators, and wrist extensors, similar to the baseball pitch. The forward and medial movement of the arm in combination with the eccentric contractions causes the arm to lose velocity (Olson & Hunter, 1987). Recently, Maffet et al., (1997), observed a decrease in muscle activity during this phase. The decrease in muscle activity was attributed to the arm lightly contacting the lateral portion of the hip following release of the ball. The contact with the hip decreases the forward momentum of the arm, therefore, less muscle involvement is needed to decelerate the arm.

Windmill Pitch Mechanics

Kinematic analyses have been performed on the windmill pitch with a primary focus on the upper extremity. Zollinger (1973) performed one of the first analyses of the windmill pitch, using one elite female pitcher. The analysis divided the pitch sequence into stance, windup, delivery and follow-through phases. The variables evaluated were stride length, velocity of the pitch, and torque applied at the shoulder and wrist. Average stride length was two thirds of the subject's standing height. Torque applied at the shoulder was approximately three times that of the torque at the wrist. It was concluded that body alignment and proper sequencing of the segments were important contributors in pitching performance.

Alexander and Haddow (1982) performed a kinematic study of a windmill pitch to determine the relative motion of the three segments of the upper extremity during the execution of the pitch. Four highly skilled pitchers (two females and two males) were chosen as subjects. Two high-speed film cameras (average film speed 1/100 frames/sec) were used to record 10 trials of each subject's "fastest" pitch. One camera was placed perpendicular to the participant and the other camera was placed to the rear. The segmental endpoints of the upper extremity (shoulder, elbow, wrist, and fingertips) were digitized separately from the whole body. The major movement pattern was in the sagittal plane, therefore a two-dimensional analysis was chosen. The study suggested that there was a specific segmental sequence of the pitching arm, which distinguished highly skilled pitchers from novice pitchers. The upper arm reaches maximum velocity first, followed by the forearm and hand. Therefore, the authors concluded that pitching performance might be dependent on the ability of the pitcher to decelerate the segments in the correct sequence in order to increase velocity of the hand at the time of ball release.

Wilson and colleagues (1985) conducted a comparative analysis of five different pitches performed by six Australian and three New Zealand pitchers. The five pitches chosen for analysis were the fastball, dropball, curveball, riseball and change-up. One high-speed camera (150 frames/sec) with a zoom lens, was placed perpendicular to the pitchers. A total of 21 points were digitized in alternative film frames. The linear velocities of the pitches were similar to those found by Alexander and Haddow (1982). The velocities were highest for the fastball and lowest for the change-up. The location of the center of gravity (COG) of the pitcher was dependent on the pitch thrown. The COG for the fastball, curveball, and change-up are in close proximity to each other. The dropball requires a slightly higher COG at ball release to achieve an effective execution of the pitch. In order to produce the downward spin for a dropball, the pitcher elevates the body to raise the throwing shoulder, and forcefully rolls the wrist over the top of the ball. In contrast, the riseball requires a lower COG at the point of release. It typically demonstrates a longer stride length and greater knee flexion of the pivot leg (Greene et al., 1994). This position allows for a lower release point, which is critical in producing the backspin to get the ball to rise. Lower extremity joint angles at ball release were also examined in this investigation. The hip, knee, and ankle angles at ball release were similar for New Zealand and Australian pitchers. The angles averaged 129°, 168° and 113°, respectively, for the New Zealand pitchers and 120°, 158° and 94°, respectively, for the Australian pitchers (Wilson et al., 1985).

Greene, Tant, and McKeon (1994) conducted a three-dimensional kinematic study comparing different pitching techniques among female and male windmill pitchers. Their results indicated that the greatest velocities of the hand were seen prior to the release of the fastball in both females and males. The lowest velocities were seen during the change-up. These findings are consistent with the results of studies by Alexander and Haddow (1982) and Wilson et al., (1985). Stride lengths varied between the different pitches indicating changes in lower body mechanics with the different pitches. The riseball exhibited the longest stride, followed by the fastball, curveball, and change-up, respectively.

In a recent study, Maffet et al., (1997) described the firing patterns of selected shoulder muscles during the windmill pitch. Fine wire electromyography was used to examine the muscle activity of the deltoid, serratus anterior, pectoralis major, and rotator cuff muscles in 10 collegiate level female pitchers. The rotator cuff and deltoid muscles were identified as being the most active during the initial half of the ascent phase. The posterior deltoid and teres minor were particularly active during the last half of the ascent phase, with assistance from the infraspinatus. The predominant muscles active in the descent phase up until ball release were the pectoralis major, subscapularis, and serratus anterior. Concurrently, the activity of the posterior deltoid, teres minor, and infraspinatus were diminished. Decreased muscle activity for all muscles except the teres minor was also exhibited in the follow-through. Deceleration of the pitching arm was initiated, as a result of light contact with the lateral portion of the hip (Maffet et al., 1997).

The results of the Maffet et al., (1997) study revealed biomechanical differences and similarities between the windmill pitch and the baseball pitch. The windmill pitch was performed with the humerus in the plane of the body whereas the humerus is abducted during the baseball pitch (Maffet et al., 1997). Softball pitchers generate their power through adduction of the arm across the body and decelerate the arm by contacting the hip after ball release. Baseball pitchers generate their force through internal rotation of the humerus, which is decreased by eccentric contraction of the muscles during the follow-through (Maffet et al., 1997). The pectoralis major is the primary force generating muscle in both types of pitches. The pectoralis major and subscapularis work together to stabilize and protect the anterior capsule from anterior translation of the humerus in baseball and softball pitchers (Maffet et al., 1997). The serratus anterior act similarly in both pitches to synchronize scapulohumeral movement (Maffet et al., 1997). These findings have important implications for diagnosis and treatment of shoulder injuries in softball pitchers.

Injury and Load

Many studies have been conducted to examine loads on the body during activities such as walking, running, jumping and landing. Limited information is available regarding loads on the body in sport specific skills. In fastpitch softball, the stresses on the shoulder have been investigated; however no information is available in the literature about loading on the lower extremity during windmill pitching.

It has been suggested that loads placed on the joints in specific sport activities be examined (Nigg, Denoth, & Neukomm, 1981). Quantification of these loadings should lead to better understanding of the forces that could potentially cause injury (Baumann, 1981; Nigg et al., 1981). The joint forces provide adequate information about the magnitude of the stresses on the lower extremity. Nigg et al., (1981) proposed that counteraction to load can be useful; however, if the load is excessive, injuries may result.

The forces encountered by the human body can be described as passive and active. Passive forces occur during a latent period followed by the active forces. Passive forces can cause microtrauma to the connective tissue and bones. Active forces occur when a movement is controlled mainly by the muscular system. Active forces are capable of causing the microtrauma, which results in acute injuries (Hamill, Bates & Knutzen, 1984). An increased understanding of the loads that are placed on the body may lead to the reduction of injury in sport through improved training and performance mechanics.

Loosli, Requa, Garrick, and Hanley (1992) conducted an injury survey of eight highly ranked teams at the 1989 women's NCAA softball tournament. The results indicated that the majority of injuries involved the upper extremity. Over 40% of the pitchers surveyed experienced an injury at some point during the season, causing them to miss practice and/or competition. More than 80% of the time-loss injuries involved the upper extremity and were classified as overuse or gradual onset injuries. Lower extremity injuries comprised approximately 30% of all injuries reported by the pitchers. The types of lower extremity injuries that were reported included ligament sprains, muscle strains, patellofemoral dysfunction and contusions.

Donovan and Toronto (1994) performed a retrospective study of 53 elite softball pitchers at an international softball tournament. The survey examined injuries incurred during the pitchers' softball careers. A total of 122 injuries were reported resulting in over 400 games missed. Almost 40% of the injuries involved the upper extremity with approximately 80% of the injuries involving the same side of the body as the pitching arm. There were three lower extremity injuries reported by the pitchers. The most common injuries reported were strains and sprains of the upper extremity associated with the pitching side, which is consistent with the results of Loosli et al., (1992).

Werner, Murray, Levy, Smith, Plancher, and Hawkins (in press) collected three-dimensional kinematic data on 26 pitchers at the 1996 Olympic Games to provide insight into the relationship between pitching mechanics and stress on the throwing shoulder. The results revealed a pronounced distraction force on the shoulder that occurs as the ball is released. The force ranged in magnitude from 50 to 150 percent of the pitcher's body weight, which is similar to the force experienced in baseball pitching.

The lower extremity is equally important in decreasing shoulder distraction and producing ball speed. Werner et al., (in press) found that as the stride leg contacts the ground the angle of the knee should be positioned in approximately 30° of flexion. A knee angle less than 30° results in additional stress on the shoulder and decreased ball speed. Stride length and proper foot placement of the stride leg are two additional factors important for decreasing shoulder distraction and producing ball speed. Furthermore, the hips should be half way closed (approximately a 45° angle) when the ball is released. Stress on the shoulder is increased when the hips are kept open at ball release.

Ground Reaction Forces

The magnitude and intensity of ground reaction forces (GRF) have implications for injury and sport performance. GRF is an external force that acts on the body. It indicates the intensity and duration of stress subjected by the body during contact with the ground. Ground reaction force is measured in vertical (VGRF), anterior-posterior (AP), and medial-lateral (ML) directions. VGRF has been shown to be the easiest to quantify due to low intersubject and intrasubject variation (Cavanagh & LaFortune, 1980; Munro, Miller, & Fuglevand, 1987). VGRF can be influenced by ground surface, running speed and style, and footwear (Cavanagh & LaFortune, 1980).

Gait

Walking

Several studies have examined the patterns of GRF and the contributing factors in walking, running, jumping and landing. Gait is the most common repetitive movement performed by humans. The earliest studies of GRF revealed only general patterns of force in walking. Elftman (1939) determined the general pattern of pressure during walking by filming people from beneath as they walked across a glass plate. The results demonstrated that initial contact occurred at the heel followed by a forward movement of the center of pressure to the toes just prior to the foot leaving the surface.

Hamill, Bates, and Knutzen (1984) investigated the symmetry of human gait. They found no significant differences in GRF between the right and left legs in walking and concluded that human gait appeared to be symmetrical. However, according to the definition of gait symmetry given by Herzog, Nigg, Read, and Olson (1989), human gait is asymmetrical. Others have found asymmetries in walking while examining muscle activity of the lower extremities (Ounpuu & Winter, 1986).

Martin and Marsh (1992) evaluated the effects of step length and step frequency on GRF during walking. Their results suggested that speed should be held constant in research studies, however, step length and frequency should not be constrained when assessing gait. Furthermore, these measurements should be reported when examining GRF and their association should be considered when interpreting GRF characteristics.

Running

Overuse injuries have been frequently associated with repetitive impact forces in various activities, particularly in running and jumping/landing (Cavanagh & LaFortune, 1980; Dufek & Bates, 1990). Cavanagh and LaFortune (1980) studied the differences between GRF and center of pressure in distance runners. The runners were classified as midfoot or rearfoot strikers. Both groups showed similar peak values in ML component, which were small in comparison with the other components. The midfoot strikers had two peaks in the AP direction (0.45 BW) and one peak in the vertical direction, with an average peak value of 2.70 times BW. The rearfoot strikers demonstrated only one peak in the AP direction (0.43 BW) and two peaks in the vertical direction of 2.20 and 2.80 times BW. The magnitudes of the AP and vertical components were not significantly different between the groups.

Munro, Miller, and Fuglevand (1987) studied the pattern of GRF in 20 male runners. The runners performed 40 trials in an effort to obtain equal contact with the right and left foot across a force platform at speeds ranging from 2.5 to 5.5 $m{\bullet}s^{-1}$. Nearly all the runners were rearfoot strikers. A double peak characterized the VGRF, which was consistent with the findings of Cavanagh and LaFortune (1980). Munro et al., (1987) observed a large impact force in the VGRF as the foot contacted the surface. This peak was referred to as the "passive peak". Following the passive peak, was a second peak in vertical force, called an "active peak". The active peak occurred as the foot pushed off the ground. The magnitude of the impact forces ranged from 1.60 BW at 3.0 $m{\bullet}s^{-1}$ to 2.30 BW at 5.0 $m{\bullet}s^{-1}$. In general, average GRF increased as running speed increased.

The AP force is characterized by a braking pattern as the foot contacts the ground (Munro et al., 1987). This braking force opposes the forward movement. In addition, a second peak is observed as the foot pushes off the ground, called a propulsive force. In comparison, Cavanagh and LaFortune (1980) reported a single peak in the AP direction for rearfoot strikers. The final component evaluated, ML force, exhibits small magnitudes and extreme variability. No direct relationship has been established between GRF in the ML direction and running speed (Munro et al., 1987).

Jump/Landing

Landing from a jump or fall creates impact forces that are absorbed by the lower extremity muscles. Dufek and Bates (1990) examined the factors that contribute to the VGRF during landing. The result of their study revealed that the strategy used during landing was an important factor in the resultant GRF. The VGRF increased with greater landing heights and stiffer landing technique. Landing with the knees fully flexed resulted in lower peak VGRF. Furthermore, there was greater reduction of VGRF in toe-heel landings as compared to the flat-foot landings.

Devita and Skelly (1992) identified and compared GRF and joint kinetics of the lower extremity during drop landing with soft and stiff landing techniques. Compared to soft landings, stiff landings were characterized by a smaller range of motion at the ankle, knee, and hip and a more upright position. This strategy resulted in more extension in the joints during floor contact. In soft landing, there was increased flexion at each joint in preparation for landing, which resulted in the body being more flexed at contact.

Sport-Specific Skills

The prevalence of injury due to overuse and repetitive impacts has prompted studies of specific sport activities. Ricard and Veatch (1990) compared the GRF of high and low impact aerobics. Five highly skilled aerobic dance instructors were asked to perform a high and low impact version of the same aerobic dance movement on a force platform. Peak impact force was 0.98 times BW (0.56 - 1.58 BW) for the low impact version and 1.98 times BW (1.02 - 2.62 BW) for the high impact step. The GRF was significantly higher in the high impact aerobic step compared to the low impact version of the same movement. However, the magnitude of force was lower than the forces reported from basketball and gymnastic landings.

Michaud, Rodriguez-Zayas, Armstrong and Hartnig (1993) also examined the GRF in high and low impact aerobics. Eight highly skilled aerobics instructors volunteered for the study. Initially, three of the eight participants were videotaped as they performed 10 high and 10 low impact aerobic movements. Seven high impact and nine low impact dance movements were selected for data analysis. Participants attended a second session to familiarize themselves with the movements and practiced landing on a force platform. In the final session, participants performed the high impact steps for several minutes, followed by a rest period, and then completed the low impact aerobic movements. VGRF and lateral GRF were collected approximately 30 seconds for each dance movement. The results of this study support the previous work of Ricard and Veatch (1990). Peak VGRF was greater in the high impact movements compared to the low impact steps (Michaud et al., 1993). The lateral impact forces were similar in both types of aerobic dance (Michaud et al., 1993). The authors recommended that low impact dance routines be emphasized over high impact aerobics, due to their low impact forces. It was suggested that these lower forces could reduce the incidence of lower extremity overuse injuries.

Ground reaction forces have been studied in volleyball to investigate the amount of risk of injury to the lower extremity involved in various volleyball skills. Adrian and Laughlin (1983) studied 15 female collegiate volleyball players as they performed blocking, spiking, and passing skills on a force platform. Peak values of VGRF for the stationary block, moving block, and spike were 3.00, 3.70, and 4.80 times BW, respectively. Peak forces for the four passing movements were not significantly different, however the data revealed shearing forces amounting to 2.00 times BW. The research provided a preliminary investigation of potential injury risks associated with various volleyball skills.

The lower extremity is profoundly vulnerable to injury in basketball. The most commonly injured joints are the ankle and knee. McClay, Robinson, Andriacchi, Frederick, Gross, Martin, Valiant, Williams, and Cavanagh (1994) collaborated on a biomechanical study of professional basketball players. GRF was collected as the players performed common basketball movements across a force platform. Peak VGRF was highest in the layup landing (8.90 BW) and lowest in running (2.50 BW). GRF in the AP and ML directions were also highest in the layup landing. The shuffle demonstrated the largest peak medial and lateral forces (1.40 and 0.01 times BW, respectively) compared to cutting and running. The high forces applied to the body during these activities may pose a potential risk of injury.

One study that examined the GRF exerted during a serve, forehand and volley in tennis indicated relatively low forces in all directions (Van Gheluwe & Hebbelinck, 1986). The authors found the greatest magnitude of force in the vertical direction, however it did not exceed one third of the body weight. Millbank and Nicol (1990) examined the impact forces during various stopping techniques in tennis. They found greater horizontal forces in conventional stopping compared to other techniques ("checking") used to stop in tennis. This suggests that greater shearing forces may occur in the joints of the lower extremity during convetional stopping.

Fink (1993) examined the joint forces on the forward leg in a fencing lunge in five participants. Two peaks in vertical force characterized the lunge. Two fencers demonstrated low peak impact forces in the vertical direction, 1.03 to 1.27 times BW. The peak impact forces during the lunge ranged from 2.24 to 3.64 times BW for the other three participants. The second peak for all fencers was relatively low compared to the initial peak. The AP forces in this activity were also small in magnitude.

Ground reaction force patterns of the push-off and landing limbs were measured in collegiate and highschool baseball pitchers (MacWilliams, Choi, Perezous, Chao, & McFarland, 1998). The investigators used a five camera video analysis system and two force platforms to measure kinematic and kinetic responses during five pitches judged to be strikes by a catcher. One force platform was placed below the pitching rubber to measure forces during the windup and the cocking phases. A second platform was used to record the landing forces during each pitch. Results of the study indicated the push off forces were gradually built up during the windup and peaked prior to foot contact, with a maximum force of -0.35 BW. After foot contact, the "braking" shear force increased rapidly and reached a maximum of 0.72 BW. The braking force was used to slow the motion of the lower limbs which was transferred to the trunk and arms. Medial-lateral shear force was negligible for both push off and landing in baseball pitching. Vertical force for the push off occurred early in the pitching cycle and had a magnitude of 1.00 BW. The vertical force in landing peaked at 1.50 BW just prior to ball release. Overall, the authors concluded that the GRF were repeatable over pitches by the same pitcher and characteristic GRF patterns were present among the group of pitchers. More importantly, push off and landing forces were correlated with wrist velocity, suggesting that leg drive influences arm velocity.

A considerable number of sport injuries result from high repetition and overuse. These injuries are often concentrated in the lower extremity due to the load bearing responsibility. Principle causes relate to the magnitude of the force(s) or the rate at which the forces are applied to the body. The extent of the force applied to the body during certain activities can be very high, such as in jumping and landing activities. In addition, injury may occur as a result of repetitive impact force applications in a relatively short period of time.

CHAPTER III

METHODS AND PROCEDURES

The purpose of this study was to determine the kinematic responses and magnitude of ground reaction forces (GRF) created by the stride leg in selected windmill pitches. The results of the research may have possible applications for identifying injury mechanisms, injury prevention, and performance enhancement for fastpitch softball pitchers. The primary focus was on the GRF generated and kinematics of the lower extremity during impact with the ground.

Subjects

Five healthy female fastpitch softball players volunteered for the study (18-35 yrs). Pitchers were either currently participating at the intercollegiate level or had competed at the intercollegiate level. Participants were physically active at least three times per week and had no history of serious orthopedic injury. They were free of injury at the time of testing.

Prior to testing, the experimental protocol was explained in verbal and written form. Participants read and signed an informed consent form, approved by the Institutional Review Board at the University of Tennessee (Appendix C), before participating in the study. The participants also completed a personal data form (Appendix D) prior to data collection.

Experimental Protocol

Participants were asked to perform five different pitches commonly used in fastpitch softball competition. The pitches included the fastball, change-up, dropball, curveball and riseball. A randomized order of the pitches was pre-determined and five trials of each pitch were performed in succession.

Data collection for each participant required one session to complete. Anthropometric measurements (height, weight, lower extremity girth and length) were recorded at the beginning of the test session. Lower extremity girth and length were collected with a cloth measuring tape for girth and a standard meter-stick for length. Measures of girth and the length of the lower extremity segments were taken three times and the mean measurement was calculated. Circumference measurements were taken for the foot, ankle, knee and upper thigh as follows:

1. Distal circumference of the stride foot was measured at the metatarsal heads of the foot.
2. Distal circumference of the lower leg was measured slightly above the lateral malleolus.

3. Proximal circumference of the lower leg was measured at the thickest portion of the gastrocnemius.
4. Distal circumference of the thigh was taken at the joint line of the knee.
5. Proximal circumference of the thigh was measured at the thickest part of the upper thigh.

Seven anatomical landmarks were identified and marked with reflective markers on the opposite side of the throwing arm. Markers were placed on the head of the fifth metatarsal, heel, lateral malleolus, tibial plateau, femoral epicondyle, greater trochanter of the femur, and the acromion. Lower extremity length measurements were then performed as follows:

1. Length of the foot segment was measured from the center of the head of the fifth metatarsal marker to the center of the lateral malleolus marker.
2. Length of the lower leg segment was measured from the center of the lateral malleolus marker to the center of the tibial plateau marker.
3. Length of the upper leg segment was measured from the center of the tibial plateau marker to the center of the greater trochanter marker.
4. Proximal height of the lateral malleolus was measured from the ground to the center of the lateral malleolus marker.

5. Ankle moment arm was measured from the center of the lateral malleolus marker to the center of the Achilles tendon.

Participants performed a stretching and pitching warm-up routine before data collection. The stretching routine included a series of upper and lower extremity exercises. The pitching routine was based on the individual's pre-game pitching warm-up routine. Following the completion of the warm-up routine, average stride length was recorded for each pitcher. The participant performed three trials of each type of pitch and stride length was measured in centimeters using a standard meter stick. The measurement was taken from the front of the lead foot in the stance position (marked with black tape) to the heel of the stride leg upon contact with the ground.

The pitchers performed several practice trials to familiarize themselves with the protocol. The pitching mark was adjusted according to stride length, in order to allow the foot of the stride leg to contact the middle of the force platform. Data collection began when the pitcher indicated she felt comfortable with landing on the force platform without targeting.

The pitchers performed five successive trials of each pitch. They were encouraged to simulate game-like intensity. Softball gloves were worn by all participants and an indoor softball (Incrediball, Easton) was pitched into a mat positioned against the wall. A target with the dimensions of a strike zone was taped to the mat. A pitch was repeated if the ball did not strike the target or if the pitcher did not feel she properly threw the pitch. The results of a pilot study indicated that pitches were more consistent after a brief practice period. Therefore, pitchers threw three to five practice pitches at the beginning of each condition.

Instrumentation

The measurement of anthropometric and biomechanical data occurred through the use of a cloth measuring tape, standard meter stick, force platform and a video camera. The experimental setup is illustrated in Figure 1 (Appendix B).

Force Platform

An AMTI force platform (Advanced Mechanical Technology Inc., OR6-7) was interfaced via an analog to digital converter (National Instruments, Inc.) to a computer to measure the ground reaction forces (GRF) and moments under the foot during the impact of the stride leg while performing the pitching trials. Forces were measured in the vertical, anteroposterior, and mediolateral directions. The pitching mark was adjusted according to stride length to allow the foot of the stride leg to contact the center of the force platform.

Force platform data were collected and stored using the Ariel Performance Analysis System (APAS). The forces were sampled for six channels using a reference system where F_x, was in the mediolateral direction, F_y represented the anteroposterior direction and F_z was the vertical force. M_x, M_y and M_z were the moments around the x, y, and z axes. Ground reaction forces were sampled under the stride foot at a frequency of 1000 Hz for a period of two seconds using the Ariel Performance Analysis System (APAS). Data collection was initiated with a trigger level of 10 Newtons (N) for the vertical channel and with foot contact with the force platform. A period of 10% of the sampling time was recorded to register the pre-contact information. The force platform and video data were synchronized via a light emitting device (LED) which was visible to the video camera and fed as a separate channel to the APAS. The data were stored and analyzed using the APAS and customized software.

Video System

One video camera (Panasonic AG-188U) was used to obtain a two-dimensional sagittal view of the participants as they performed each trial. Camera shutter speed was set at 1/2000 second and frame rates of 60 Hz. The camera was positioned perpendicular to the pitcher's main plane of motion at a distance of seven meters. Prior to data collection, seven reflective markers were placed on the non-throwing side of the participant. Markers were placed on the shoulder (distal to acromion), hip (greater trochanter), knee (femoral epicondyle and tibial plateau), ankle (lateral malleolus), forefoot (head of the fifth metatarsal) and heel (parallel to the head of the fifth metatarsal). In addition to the seven anatomical markers, the softball was marked with reflective tape in order to estimate ball release velocity. A fixed reflective marker was used as the origin of the kinematic reference system. The marker was visible to the camera throughout the pitching motion. The images of the markers were recorded on tape and later digitized to obtain anatomical coordinates using APAS.

Data Processing

Force Platform Data

Force platform data were collected and stored using the Ariel Performance Analysis System (APAS). The forces were reported using a reference system established on the center of the force platform where $F_{x,}$ represented the mediolateral direction (toward firstbase), F_y the anteroposterior direction (towards homeplate), and F_z the vertical force. The moments around the x, y, and z axes were indicated as $M_{x,}$ M_y and $M_{z.}$

The force and moment signals were converted to Newtons (N) and Newton x meter (Nm) using conversion factors derived from parameters provided by the manufacturer and the amplification gains set for each of the six channels (1000 Hz). The force and moment values were normalized by the pitcher's body mass, resulting in units of Nkg^{-1} and $Nmkg^{-1}$, respectively.

Kinematic Data

Seven anatomical landmarks were identified with reflective markers to define four segments of the body. Each segment was described by markers placed on proximal and distal ends: the trunk was defined by the acromion and greater trochanter markers, the thigh segment by the greater trochanter and the femoral epicondyle markers, the leg by the femoral epicondyle and the lateral malleolus markers, and the foot segment by the lateral malleolus and the head of the fifth metatarsal markers. An additional marker was used on the softball to estimate the velocity of the ball after it was released.

A reference frame (1.555 m x 1.255 m) was recorded at the beginning of a data collection session. The average of digitized x and y distances were used as scales to convert the horizontal and vertical coordinates of each individual marker from image reference system to lab reference system.

Kinematic data were smoothed with a zero-lag, fourth order Butterworth low-pass filter. The optimal cutoff frequency was computed according to the algorithm by Jackson (1979). The smoothed coordinates were used to compute linear and angular kinematic time-history in a customized computer program. Linear and angular velocities and accelerations were calculated for the lower extremity using the polynomial method (Jackson, 1979). The angular position data for the hip, knee and foot were also smoothed using the optimal digital filter.

Synchronization

Synchronization between the kinematic and analog signals was accomplished by the use of a LED, which was visible to the video camera and sampled as a separate channel of the analog signal. The LED was triggered with a low level of threshold (10 N) at foot contact with the force platform. A visual signal was sent to the video camera while an analog signal was sampled through a separate channel by the APAS.

The purpose of the study was to determine the kinematic responses and magnitude of ground reaction forces created by the stride leg in selected windmill pitches. Force platform and kinematic data were digitized and processed with customized software. The data were used to calculate kinematic variables.

Statistical Analysis

Descriptive statistics (mean and standard deviation) were computed on all descriptive variables. Separate single factor analyses of variance (ANOVA) were used to evaluate individual and group differences for the primary kinematic and kinetic variables.

Statistical procedures were performed using the GLM procedure in the Statistical Analysis System (SAS). Differences were considered to be significant at $p < 0.05$.

CHAPTER IV

RESULTS

The purpose of this study was to determine the kinematic responses and magnitude of ground reaction forces (GRF) created by the stride leg in selected windmill pitches. The primary focus was on the GRF generated and kinematics of the lower extremity during impact with the ground.

Demographic Information

Five female fastpitch softball pitchers (height 1.76 m ± .11 m; mass 68.99 kg ± 9.63 kg) gave informed consent and were accepted to participate in the study. The informed consent was approved by the Institutional Review Board. The subject age range was 19 to 27 years and the mean age was 22.5 years (± 3.65 yr). All pitchers were right-handed. All five subjects performed five trials of a fastball (FB), change-up (CH), dropball (DB) and riseball (RB). In addition, two of the pitchers threw five curveballs (CB). Subjects had a total of 63 years of pitching experience (mean 12.6 yr ± 4.72 yr) and 17 years of intercollegiate pitching experience (mean 3.2 yr ± 1.48 yr). The descriptive and physical characteristics of the five subjects are presented in Table 1 (Appendix A).

Kinematics

Stride Length Characteristics

Stride length was measured as the horizontal distance between heel of the stride foot at touchdown and the front edge of the pitching rubber for each type of pitch. Pitchers performed three trials of each pitch and the average distance was recorded. Mean stride lengths for each pitch are represented in Figure IV.1. The stride length characteristics indicated different strategies were used by pitchers for different pitches. The participants exhibited average stride lengths of 134.33 cm (± 6.41 cm) for fastball (FB), 113.80 cm (± 27.09 cm) for change-up (CH), 120.13 cm (± 14.37cm) for dropball (DB), 123.46 cm (± 7.14 cm) for curveball (CB) and 138.97 cm (± 9.08 cm) for riseball (RB). Individual and group stride length characteristics are listed in Table 2 (Appendix A).

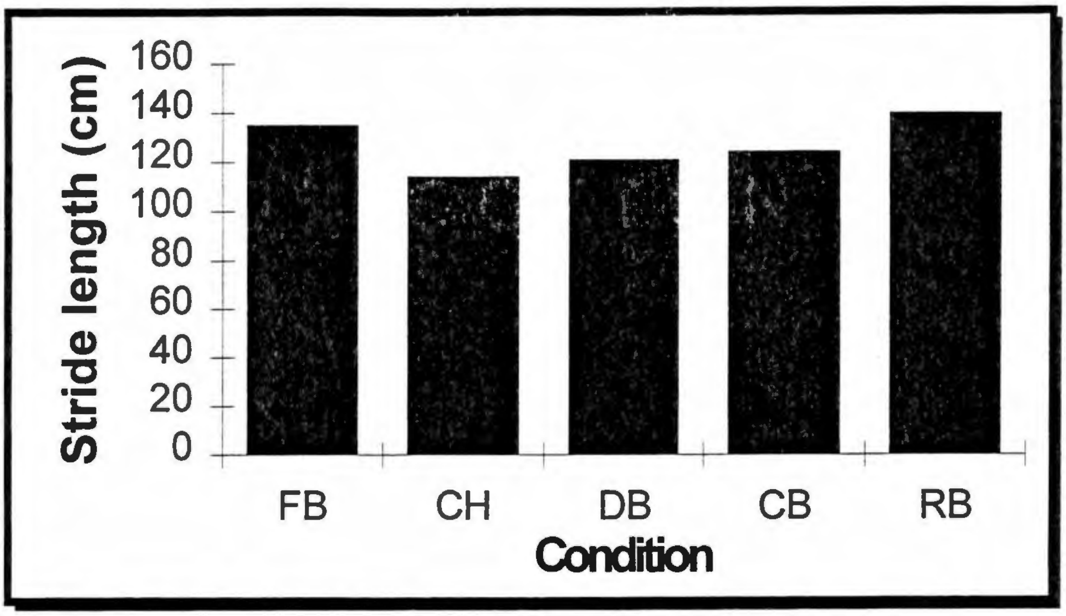

Figure IV.1. Mean stride length for each condition (cm).

Ball Velocity

Five trials for every pitch and every pitcher were recorded and digitized to obtain ball velocity at the time of release. The release velocity for each pitch was estimated using the ball coordinates obtained through digitization for three consecutive frames following ball release. Due to the limitations of a single camera view, the ball was hidden by the body in some pitches, therefore ball velocities were not estimated for these trials.

Mean ball release velocities are represented in Figure IV.2. The fastest ball release velocity was demonstrated by the CB 20.4 $m{\bullet}s^{-1}$ (± 3.66 $m{\bullet}s^{-1}$) followed by the FB 20.3 $m{\bullet}s^{-1}$ (± 2.04 $m{\bullet}s^{-1}$), RB 19.7 $m{\bullet}s^{-1}$ (± 1.69 $m{\bullet}s^{-1}$), DB

19.6 $m \cdot s^{-1}$ (± 1.43 $m \cdot s^{-1}$) and CH 14.4 $m \cdot s^{-1}$ (± 1.24 $m \cdot s^{-1}$). Means and standard deviations for ball release velocities are listed in Table 3 (Appendix A).

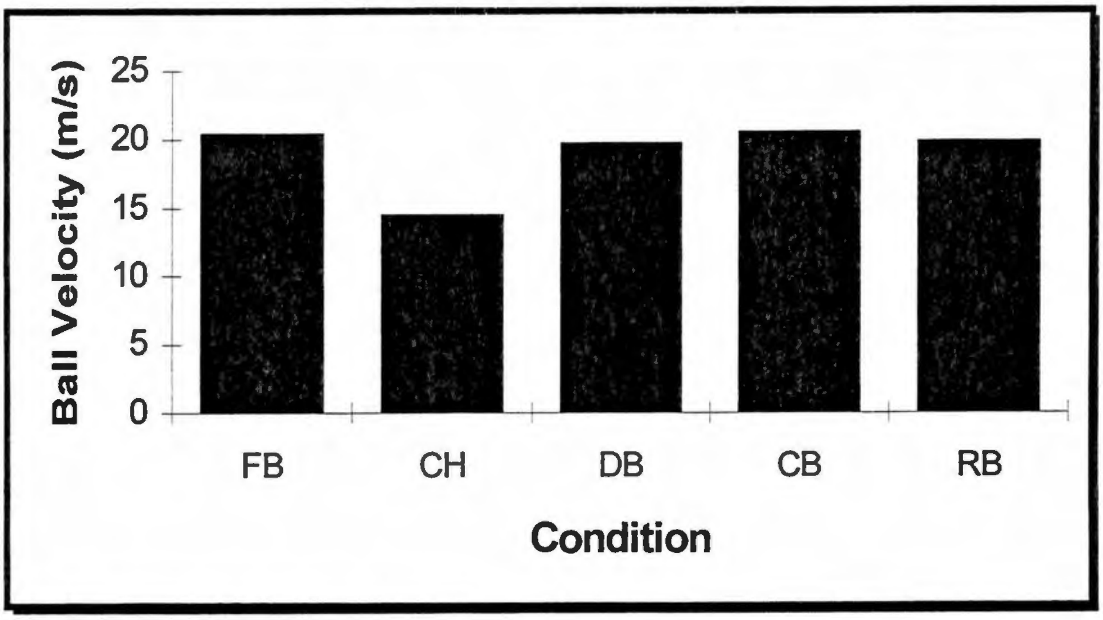

Figure IV.2. Mean ball release velocity for each condition (m/s).

Statistical Procedures

A total of five kinematic variables were established from videography for the hip, knee and ankle. The five variables include joint angle at contact (JAC), maximum angle achieved during motion (MAX), time to maximum angle (TMAX), minimum angle achieved during the motion (MIN) and time to minimum angle (TMIN). Single factor ANOVAs were performed on each of the five variables. The initial single factor ANOVA (pitch) compared kinematic variables between pitches for the hip, knee and ankle. A second ANOVA (pitcher) was performed to compare differences among pitchers for each type of pitch. Level of significance for all comparisons was established at

$p < 0.05$. Several individual differences were demonstrated in the measured variables for the different pitches. Therefore, in the following sections, a break down of each condition follows a general description of each joint. Differences between participants within each condition were examined using a Tukey's Post Hoc Comparison ($p < 0.05$). Only those differences that are significant were reported within each condition. Statistical comparisons using means and standard deviations for the hip, knee and ankle for all conditions are presented in Table 4 (Appendix A). Figures 2-6 (Appendix B) represent a comparison of the hip, knee and ankle in each of the five pitches for each individual variable.

Hip

ANOVA results demonstrated a significant effect on JAC ($F= 3.56$; $p= 0.009$), MAX ($F= 3.65$; $p= 0.008$), and MIN ($F= 10.03$; $p= 0.0001$) across all conditions (pitches). A Tukey's post hoc comparison revealed the main difference in JAC occurred between the FB and the CH, with angles being 23.01 and 14.88° of flexion, respectively. Mean MAX hip angle in the CH (15.43°) was significantly lower than the CB, FB, RB, and DB (23.73, 23.15, 21.98 and 21.37°, respectively). The MIN hip angle for the CH (12.63°) was also significantly lower than the RB, FB, DB and CB (17.45, 17.96, 18.40 and 21.08°, respectively).

Fastball

Individual means and standard deviations for the hip in the fastball are presented in Table 5a (Appendix A). ANOVA (subject) results demonstrated a significant effect within the FB for MIN ($F= 23.03$; $p= 0.0001$) and TMIN ($F= 3.87$; $p = 0.017$). MIN hip angle of subject 3 (S3), 11.44° was significantly lower than MIN hip angle of subject 2 (S2), subject 1 (S1), subject 4 (S4), and subject 5 (S5) (22.18, 20.98, 18.81 and 16.44°, respectively). Significant differences were also demonstrated between S5 (16.44°) and S2 and S1 (22.18 and 20.98°). MIN hip angle occurred significantly earlier in the motion in S4 (76 ms) as compared to S1 and S5 (139 ms), which occurred later in the motion.

Change-Up

Individual means and standard deviations for the hip in the change-up are presented in Table 6a (Appendix A). Comparisons of pitchers within the CH revealed significant differences in JAC ($F= 54.24$; $p= 0.0001$), MAX ($F= 47.72$; $p= 0.0001$), TMAX ($F= 5.30$; $p= 0.004$), MIN ($F= 11.52$; $p= 0.0001$) and TMIN ($F= 4.85$; $p= 0.006$). S1 (22.39°) demonstrated a significantly higher JAC than S2, S5, S4 and S3 (14.29, 12.99, 12.77 and 12.01°, respectively). MAX hip angle of S1 (22.39°) was significantly higher than MAX angles of S2, S3, S4 and S5 (14.62, 14.03, 13.15 and 12.99°, respectively). The only difference in TMAX occurred between S1, S5, and S3. MAX hip angle for S1 and S5 occurred at contact which is significantly earlier than S3 (113 ms). MIN hip angle for S1 (15.99°) was significantly higher than S2, S3, S4, and S5 (12.98, 11.83, 11.66 and 10.72°). TMIN was significantly different between S3 (43 ms) and S1 (163 ms).

Dropball

Individual means and standard deviations for the hip in the dropball are presented in Table 7a (Appendix A). Comparisons of participants within the DB revealed significant differences in JAC (F= 44.02; p= 0.0001), MAX (F= 66.94; p= 0.0001), TMAX (F= 13.16; p= 0.0001), MIN (F= 22.29; p= 0.0001) and TMIN (F= 15.69; p = 0.0001). S3 (13.30°) demonstrated a significantly lower JAC than S1, S2, S5 and S4 (26.71, 24.36, 19.08 and 17.16°, respectively). In addition, mean JAC for S1 and S2 (26.71 and 24.36°) was significantly higher than S5 and S4 (19.08 and 17.16°). Similarly, MAX hip angle of S3 (14.27°) was significantly lower than S1, S2, S5 and S4 (26.74, 24.60, 21.09 and 20.17°, respectively). In addition, mean MAX hip angle for S1 and S2 (26.74 and 24.60°) are significantly higher than S5 and S4 (21.09 and 20.17°). TMAX for S5 and S4 (123 ms) occurred later in the pitching motion than S3, S1 and S2 (50, 37 and.30 ms). MIN hip angle for S3 (11.83°) was significantly lower than S2, S1, S5 and S4 (22.71, 21.46, 18.92 and 17.09°). Minimum hip angle occurred later in the pitching motion for S1, S2 and S3 as compared to S5 and S4. Mean TMIN angle for S1, S2 and S3 (160, 110 and 100 ms) were significantly different than S5 and S4 (30 and 23 ms).

Curveball

Individual means and standard deviations for the hip in the curveball are presented in Table 8a (Appendix A). Comparisons of pitchers within the CB revealed significant differences in JAC (F= 22.45; p= 0.001), MAX (F= 24.85; p= 0.001) and MIN (F= 30.19; p= 0.0006). S1 and S5 are the only pitchers in the group that threw a curveball, therefore the comparisons were limited to these two individuals. JAC for S1 (26.70°) was significantly larger than S5 (19.34°). MAX hip angle of S1 (26.70°) was significantly larger than S5 (20.73°). MIN hip angle was significantly smaller in S5 (18.21°) as compared to S1 (23.97°).

Riseball

Individual means and standard deviations for the hip in the riseball are presented in Table 9a (Appendix A). Comparisons of participants within the RB revealed significant differences in JAC (F= 3.92; p= 0.016), MAX (F= 4.10; p= 0.013) and MIN (F= 39.69; p= 0.0001). The only significant difference in JAC occurred between S2 (32.60°) and S3 (13.32°). S2 and S3 were also significantly different in MAX hip angle, 33.18 and 13.78°, respectively. Mean MIN hip angle for S3 (10.99°) was significantly lower than S2, S1 and S4

(23.96, 23.30 and 15.51°). MIN hip angle for S5 (13.51°) was significantly lower than S2 and S1 (23.96 and 23.30°).

Knee

ANOVA results demonstrated a significant effect on JAC (F= 4.06; p= 0.004), MAX (F= 6.20; p= 0.0002), TMAX (F= 15.37; p= 0.0001), MIN (F= 3.80; p= 0.006). A Tukey's post hoc comparison revealed the main difference in JAC occurred between the CB and the CH, with angles being 11.32 and 6.52° of flexion, respectively. Mean MAX knee angle in the CH (21.03°) was significantly greater than the RB, DB, CB and FB (17.04, 16.05, 15.91 and 14.97°, respectively). TMAX for the CH (153 ms) was higher than RB, CB, DB and FB (127, 118, 118 and 113 ms). The MIN knee angle for the CB (11.22°) was significantly lower than CH (6.52°), which both occurred at contact.

Fastball

Individual means and standard deviations for the knee in the fastball are presented in Table 5b (Appendix A). ANOVA results demonstrated a significant effect within the FB for JAC (F= 6.46; p= 0.001), MAX (F= 10.54; p= 0.0001), TMAX (F= 17.30; p= 0.0001), MIN (F= 6.80; p= 0.001) and TMIN

(F= 15.65; p= 0.0001). Differences in JAC occurred between S1 (11.87°) and S4 and S3 (7.68 and 5.68°) and between S2 (10.01°) and S3 (5.68°). S2, S4 and S1 (18.11, 16.57 and 15.52°) had a larger MAX angle than S5 (10.54°). In addition, S2 (18.11°) was larger than S3 (14.15°). TMAX for S5 (76 ms) occurred much quicker in the pitching motion than in S4, S2, S3 and S1 (133, 127, 133 and 113 ms). MIN knee angle occurred at the point of contact for every subject except S5, which occurred 116 ms. Significant differences in MIN knee angle occurred between S1 (11.87°) and S4 and S3 (7.68 and 5.68°) and between S2 (10.01°) and S3 (5.68°). As mentioned previously, TMIN occurred at the point of contact for S1, S2, S3 and S4 (17 ms), which was significantly earlier in the motion as compared to S5 (117 ms).

Change-up

Individual means and standard deviations for the knee in the CH are presented in Table 6b (Appendix A). Comparisons of pitchers within the CH revealed significant differences in JAC (F= 3.18; p= 0.035), MAX (F= 6.25; p= 0.002), TMAX (F= 3.70; p= 0.020) and MIN (F= 3.18; p= 0.035). The only significant difference that occurred in JAC was between S2 (10.04°) and S3 (4.63°). S2 had the largest MAX knee angle, 28.03° of flexion, and was significantly larger than S1 and S4 (15.36 and 14.72°). There were no differences in TMAX except between S1 and S3 (163 and 140 ms). MIN knee angle occurred at contact (JAC) for all five pitchers.

Dropball

Individual means and standard deviations for the knee in the DB are presented in Table 7b (Appendix A). Comparisons of pitchers within the DB revealed significant differences in JAC (F= 26.33; p= 0.0001), MAX (F= 15.59; p= 0.0001), TMAX (F= 4.06; p= 0.014) and MIN (F= 17.05; p= .0001). S5 and S2 (12.56 and 10.26°) demonstrated a significantly higher JAC than S4 and S3 (6.26 and 4.14°). In addition, mean JAC for S5 (12.56°) was significantly higher than S1 (8.46°). MAX knee angle for S5 (20.96°) was significantly higher than S4, S3, and S1 (16.76, 13.35, and 11.49°). MAX knee angle for S1 (11.49°) was significantly smaller than MAX for S5, S2 and S4 (20.96, 17.71 and 16.76°). The only significant difference in TMAX was between S4 and S1 (140 and 0.96 ms). MIN knee angle for S5 and S2 (12.56 and 10.27°) was significantly larger than S4 and S3 (6.29 and 4.14°). In addition, MIN angle for S5 (12.56°) was larger than S1 (7.51°).

Curveball

S1 and S5 were the only pitchers in the group that threw a curveball, therefore the comparisons were limited to these two subjects. There were no significant differences between these individuals for any of the kinematic variables. Individual means and standard deviations for the knee in the CB are presented in Table 8b (Appendix A).

Riseball

Individual means and standard deviations for the knee in the RB are presented in Table 9b (Appendix A). Comparisons of pitchers within the RB revealed significant differences in JAC (F= 19.10; p= 0.0001), MAX (F= 20.77; p= 0.0001) and MIN (F= 19.10; p= 0.0001). S1 demonstrated the largest JAC, 14.38°, which was significantly larger than S5, S4 and S3 (8.97, 4.68, and 4.22°). S2 (12.30°) was significantly larger than S4 and S3 (4.68 and 4.22°) and S5 (8.97°) was larger than S3 (4.22°). Mean MIN knee angle, which occurred at contact, revealed smaller angles for S5, S4 and S3 (8.97, 4.68 and 4.22°) as compared to S1 (14.38°). In addition, S4 and S3 (4.68 and 4.22°) demonstrated significantly smaller MIN knee angles than S2 (12.30°), as did S3 (4.22°) compared to S5 (8.97°). Since MIN angles for all five pitchers occurred at contact, mean TMIN between individuals was not significant for this pitch.

Ankle

ANOVA results demonstrated a significant effect on MAX (F= 5.96;

p= 0.0002) and MIN (F= 4.95; p = 0.001) variables. In the case of the ankle angles, a positive number corresponds to dorsiflexion (DF) and a negative number corresponds with plantarflexion (PF). A Tukey's post hoc comparison revealed the main difference in MAX ankle angle occurred between the CH (8.85°) and the CB, RB, FB and DB (8.35, 3.16, 3.02 and 2.18°). Significantly, less PF was demonstrated in the RB (-8.72°) as compared to the CH and DB (-18.02 and -16.15°).

Fastball

Individual means and standard deviations for the ankle in the FB are presented in Table 5c (Appendix A). ANOVA results demonstrated a significant effect within the FB for JAC (F= 5.18; p= 0.005), MAX (F= 8.52; p= 0.0003), TMAX (F= 113.29; p= 0.0001), MIN (F= 3.89; p= 0.017) and TMIN (F= 17.01; p= 0.0001). S5, S3, S4 and S2 all contacted the force platform in PF while S1 contacted in DF. JAC for S1 (6.46°) was significantly different from than JAC for S4 and S2 (-15.03 and -19.25°). S5 reached a MAX ankle angle of 12.27° of DF, which is significantly different from the MAX ankle angle for S2, S4 and S3 (0.75, -2.08 and 2.28°). Several differences occurred between pitchers in TMAX. MAX angle for S1 occurred at contact, which is significantly earlier than S2, S4, S3 and S5 (133, 133, 120 and 103 ms). TMAX was the same for both S2 and S4 (133 ms), which was significantly later in the pitching motion than S5 (103ms). Differences in MIN ankle angle were found only between S1 (-3.22°) and S2 (-19.25°). TMIN for S1 (123 ms) was significantly different from that of the other four pitchers. MIN ankle angle for S2 and S3 was measured at contact and TMIN for S5 and S4 (40 and 23 ms) occurred slightly later in the motion as compared to S2 and S3.

Change-up

Individual means and standard deviations for the ankle in the CH are presented in Table 6c (Appendix A). Comparisons of pitchers within the CH revealed significant differences in JAC ($F= 67.54$; $p= 0.0001$), TMAX ($F= 338.84$; $p= 0.0001$), MIN ($F= 24.39$; $p= 0.0001$) and TMIN ($F= 687.82$; $p= 0.0001$). JAC for S1 (12.35°) was significantly different than S3, S5, S2 and S4 (-14.08, -22.10, -23.24 and -28.05°). S3 landed with less plantarflexion (-14.08°) than S2 and S4 (-23.24 and -28.05°). MAX ankle angle occurred at contact for S1 and was earlier than S4, S2, S5 and S3 (163, 160, 147 and 140 ms). Differences in TMAX also were present between S3 (140 ms) and S4 and S2 (163 and 160 ms) and between S4 (163 ms) and S5 (147 ms). S1 (-2.64°) had a significantly different MIN ankle angle than the rest of the group. S3, S5, S2 and S4 had MIN angles of -14.08, -22.10, -23.24 and -28.05° of plantarflexion. Other differences were present between S3 (-14.08°) and S2 and S4 (-23.24 and -28.05°). TMIN for S2, S3, S4 and S5 (167 ms) was significantly different than S1 (123 ms).

Dropball

Individual means and standard deviations for the ankle in the DB are presented in Table 7c (Appendix A). Comparisons of participants within the DB revealed significant differences in JAC ($F= 49.53$; $p= 0.0001$), MAX ($F= 43.77$; $p= 0.0001$), TMAX ($F= 350.35$; $p= 0.0001$), MIN ($F= 18.03$; $p= 0.0001$) and TMIN ($F= 1227.52$; $p= 0.0001$). Once again, S1 was different from the rest of the group at contact, landing with DF as compared to PF of the ankle. JAC for S1 (6.72°) was significantly different than S3, S5, S2 and S4 (-11.43, -16.02, -17.55 and -27.93°). S4 landed with significantly more PF of the ankle than S3, S5 and S2 (-11.43, -16.02 and -17.55°). MAX ankle angle of S3 (-4.64°) was significantly different from S5, S1, S4 and S2 (9.42, 6.72, 0.18 and -0.76°). Other differences were present between S5 and S1 (9.42 and 6.72°) and S4 and S2 (0.18 and -0.76°). TMAX for S1 (16 ms) occurred significantly earlier than in S4, S2, S5 and S3 (146, 133, 123 and 120 ms). Other differences were present between S4 (146 ms) and S2, S5 and S3 (133, 123 and 120 ms) and also between S2 and S3 (133 and 120 ms). MIN angle for S4 (-27.93°) was significantly different from S1, S3, S5 and S2 (-7.86, -11.43, -16.02 and -17.55°). Differences also occurred between S1 (-7.86°) and S5 and S2 (-16.02 and -17.55°). TMIN angle for S1 (160 ms) is significantly different from S2, S3, S4 and S5 (16 ms).

Curveball

Individual means and standard deviations for the ankle in the CB are presented in Table 8c (Appendix A). Comparisons of pitchers within the CB revealed significant differences in JAC (F= 77.63; p= 0.0001), MAX (F= 11.50; p= 0.009), TMAX (F= 118.88; p= 0.0001), MIN (F=26.23; p= 0.0009) and TMIN (F= 340.59; p= 0.0001). JAC for S1 (6.63°) was significantly different from S5 (-18.40°). MAX angle for S1 (6.63°) occurred at contact and was significantly different from S5 (10.07°). TMIN occurred at contact in S1 (16 ms) and was significantly earlier in the pitching motion as compared to S5 (140 ms). MIN angles were also significantly different between S1 and S5 (-4.16 and -18.40°). S5 demonstrated MIN angle at contact, whereas TMIN for S1 was later in the pitching motion (160 ms).

Riseball

Individual means and standard deviations for the ankle in the RB are presented in Table 9c (Appendix A). Comparisons of pitchers within the RB revealed significant differences in JAC (F= 23.68; p= 0.0001), MAX (F= 39.28; p= 0.0001), TMAX (F= 12.55; p= 0.0001), MIN (F= 11.04; p= 0.0001) and TMIN (F=19.58; p= 0.0001). JAC in S1 and S4 (7.61 and .03°) landed in DF and were significantly different than S3, S5 and S2 (-10.42, -14.14 and

-14.47°). MAX ankle angle for S5 and S1 (11.33 and 7.61°) were significantly different than S4, S2 and S3 (1.51, -1.53 and -3.07°). In addition, S4 (1.51°) was significantly different than S3 (-3.07°). TMAX occurred at contact in S1 (16 ms) and was significantly earlier in the pitching motion as compared to S5, S2 and S3 (130, 123 and 120 ms). TMAX for S4 was significantly different than S5 and S2 (130 and 123 ms). MIN ankle angle for S4 (-1.81°) was significantly different than S3, S5 and S2 (-10.42, -14.14 and -14.47°). MIN ankle angle for S1 (-2.79°) was significantly different than S5 and S2 (-14.14 and -14.47°). TMIN for S3, S2 and S5 occurred at contact, which was significantly different from S1 and S4 (93 and 60 ms).

Group Comparisons

The data revealed similarities in the kinematic and kinetic variables for two pitchers S2 and S3, therefore the data of these two individuals were combined and compared to the data of the remaining pitchers. Group 1 (G1) consisted of S1, S4 and S5, whereas Group 2 (G2) consisted of S2 and S3. The same five kinematic variables for the hip, knee and ankle were examined for the two groups. In review, the five variables included joint angle at contact (JAC), maximum angle achieved during motion (MAX), time to maximum angle (TMAX), minimum angle achieved during the motion (MIN) and time to minimum angle (TMIN).

Single factor ANOVAs were performed on each of the five kinematic variables. The initial single factor ANOVA (pitch) compared kinematic variables between pitches for the hip, knee and ankle for the groups. A second ANOVA (groups) was performed to compare differences between G1 and G2 for each type of pitch. The pitchers in G2 did not throw a curveball therefore no comparisons were made between G1 and G2 for this pitch condition. Level of significance for all comparisons was established at $p < 0.05$. Differences between and within the groups for each pitch condition were examined using a Tukey's Post Hoc Comparison ($p < 0.05$). Only those differences that were significant are reported for each condition.

<u>Hip</u>

ANOVA results for G1 demonstrated a significant effect on JAC ($F= 5.01$; $p= 0.001$), MAX ($F= 7.83$; $p= 0.0001$), TMAX ($F= 5.21$; $p= 0.001$), MIN ($F= 11.59$; $p= 0.0001$) and TMIN ($F= 3.12$; $p= 0.020$). JAC was significantly different between CH (16.04°) and CB (23.03°), DB (20.98°) and FB (22.51°) within G1 among the different pitches. MAX hip angle achieved in the CH (16.17°) was significantly lower than CB, FB, DB and RB (23.73, 22.72, 22.66 and 20.98°). TMAX in the DB occurred significantly later than CH. FB and RB (31, 34 and 36 ms). MIN hip angle was significantly smaller in the CH (12.78°) as compared to CB, DB, FB and RB (21.08, 19.15, 18.74 and 17.44°).

MIN angle occurred earlier in DB (71 ms) as compared to RB and CH (125 and 124 ms).

Comparisons between the different pitches within G2 revealed significant differences for only two of the variables. Differences were present in TMAX ($F= 6.61$; $p= 0.001$) and TMIN ($F= 3.37$; $p= 0.028$). TMAX hip angle occurred significantly later in the CH (105 ms) as compared to RB, DB and FB (40, 40 and 38 ms). Differences in TMIN occurred only between FB (118 ms) and CH (63 ms).

Change-up - Inter-group Comparisons

ANOVA results demonstrated a significant effect for the CH for TMAX ($F= 16.97$; $p= 0.0004$) and TMIN ($F= 9.03$; $p= 0.0063$). Mean TMAX for the hip in G1 (31 ms) happened significantly earlier in the motion than G2 (105 ms). TMIN for the hip in G1 (124 ms) occurred significantly later in the motion than in G2 (63 ms).

Dropball - Inter-group Comparisons

Significant differences were present between G1 and G2 for the DB on only one variable, TMAX ($F=9.59$; $p= 0.005$). TMAX occurred significantly earlier in the pitch for G2 (40 ms) than for G1 (94 ms), opposite of the CH.

Knee

ANOVA results for G1 demonstrated a significant effect on JAC (F= 5.43; p= 0.0008), TMAX (F= 9.19; p= 0.0001), and MIN (F= 4.78; p= 0.001) variables. JAC in the CH (5.44°) was significantly smaller than CB, FB, RB and DB (11.32, 9.71, 9.33 and 9.09°) within Group 1 between different pitches. TMAX in the CH (155 ms) occurred significantly later than DB, CB and FB (120, 118 and 107 ms). In addition, MAX knee angle during the RB (133 ms) occurred significantly later than the FB (107 ms). MIN knee angle in the CH (5.99°) occurred at the point of contact and was significantly smaller compared to CB, RB and FB (11.33, 9.33 and 9.28°).

Comparisons between the different pitches within G2 revealed significant differences for only two of the variables. Differences were present in MAX (F= 8.94; p= 0.0001) and TMAX (F= 19.11; p= 0.0001). MAX knee angle during the CH (25.45°) was significantly larger than during RB, FB and DB (17.61, 16.13 and 15.53°). TMAX of knee angle occurred significantly later in the CH (150 ms) compared to FB, RB and DB (120, 116 and 115 ms).

Change-up - Inter-group Comparisons

Significant group differences in CH were present only for MAX (F= 8.40; p= 0.008). Mean MAX for the knee in G2 (25.45°) was significantly larger than that for G1 (18.01°).

Riseball - Inter-group Comparisons

Comparisons between G1 and G2 for the RB revealed significant differences in TMAX (F= 5.30; p= 0.030). MAX knee angle during the RB for G1 (133 ms) occurred significantly later compared to that for G2 (116 ms). TMIN for both groups occurred at 16 ms in this condition.

Ankle

ANOVA results for G1 demonstrated a significant effect for one variable, MIN (F= 3.97; p= 0.0061). MIN ankle angle revealed that pitchers in G1 landed with significantly less plantarflexion in the RB (-6.24°) compared to CH and DB (-17.59 and -17.27°).

Comparisons between the different pitches within G2 revealed significant differences for only two of the variables. Differences were present in MAX (F= 11.08; p= 0.0001) and TMAX (F= 14.11; p= 0.0001), similar to the knee. MAX ankle angle in the CH (7.90°) demonstrated significantly more dorsiflexion compared to the FB, RB and DB (-0.77, -2.30 and -2.70°), which demonstrated more plantarflexion during the pitches. TMAX ankle angle occurred significantly later in the CH (150 ms) compared to DB, FB and RB (120, 126 and 121 ms).

Fastball - Inter-group Comparisons

Comparisons between G1 and G2 for the FB revealed significant differences in MAX (F= 5.49; p= 0.028), TMAX (F= 6.27; p= 0.019) and TMIN (F= 7.02; p= 0.014). MAX ankle angle for G1 (5.55°), reached significantly more dorsiflexion in the pitch compared to G2 (-0.77°). MAX angle occurred significantly earlier in the pitch in G1 (84 ms) than in G2 (126 ms). MIN ankle angle in G1 (52 ms) occurred significantly later in the pitch compared to G2 (16 ms).

Change-up – Inter-group Comparisons

Significant differences in CH were present only for TMIN (F= 4.56; p= 0.043). MIN ankle angle occurred significantly later in the pitch for G1 (52 ms) compared to G2 (16 ms).

Dropball - Inter-group Comparisons

Comparisons between G1 and G2 for the DB revealed significant differences in MAX (F= 26.97; p= 0.0001) and TMIN (F= 4.58; p= 0.043). MAX ankle angle for G1 (5.44°), reached significantly more dorsiflexion in the pitch compared to G2 (-2.70°). MIN angle for G1 (64 ms) occurred significantly later in the pitching motion compared to G2 (16 ms).

Riseball - Inter-group Comparisons

Comparisons between G1 and G2 for the RB revealed significant differences in JAC (F= 8.78; p= 0.0070), MAX (F= 33.00; p= 0.0001), TMAX (F= 7.11; p= 0.0138), MIN (F= 6.26; p= 0.0199) and TMIN (F= 10.51; p= 0.003). Significantly less plantarflexion was present at the point of contact for GI (-2.17°) compared to G2 (-12.44°). MAX ankle angle reached significantly more dorsiflexion in G1 (6.81°) compared to G2 (-2.30°). TMAX for G1 (70 ms) was significantly different than G2 (121 ms). G1 (-6.25°) had a MIN ankle angle that demonstrated significantly less dosriflexion than for G2 (-12.44°). MIN ankle angle occurred significantly earlier in G2 (16 ms) than G1 (56 ms).

Kinetics

A total of three kinetic variables were examined in this study. The three variables included first maximum force (F1), second maximum force (F2), and maximum breaking force (F_b). The initial single factor ANOVA (condition) compared kinetic variables between pitches. A second single factor ANOVA (pitchers) was performed to compare force variable differences between pitchers for each type of pitch. Level of significance for all comparisons was established at $p < 0.05$. Several individual differences were demonstrated in the force variables for each pitch. Therefore, the following break down represents a general description of each condition. Differences between the pitchers within each condition were examined using a Tukey's Post Hoc Comparison ($p < 0.05$). Only those differences that were significant are reported for each condition.

Comparisons between the different pitches revealed significant differences in F1 (F= 9.45; p= 0.0001), F2 (F= 4.44; p= 0.0023), and F_b (F= 20.63; p= 0.0001). The negative sign in F_b represents the direction of the reactions of force. A Tukey's post hoc comparison revealed differences in F1 occurred between RB (25.18 Nkg^{-1}) and DB, CB and CH (16.67, 14.68 and 10.89 Nkg^{-1}). In addition, FB and CH (19.50 and 10.89 Nkg^{-1}) were significantly different from one another. Differences in F2 were demonstrated between FB (25.44 Nkg^{-1}) and RB, CH and CB (21.62, 20.57 and 20.04 Nkg^{-1}). F2 was larger than F1 in all conditions but RB, where F1 was larger than F2.

Several differences were present in maximum braking force. F_b in the CH (-8.44 Nkg^{-1}) was lower than DB, FB and RB (-12.19, -14.24 and -16.43 Nkg^{-1}); CB (-10.60 Nkg^{-1}) was lower than FB and RB (-14.24 and -16.43 Nkg^{-1}); and DB (-12.19 Nkg^{-1}) was smaller than RB (-16.43 Nkg^{-1}). Statistical comparisons using means and standard deviations GRF variables for all conditions are presented in Table 10 (Appendix A). Figure IV.3 represents mean peak vertical and braking force variables for each condition.

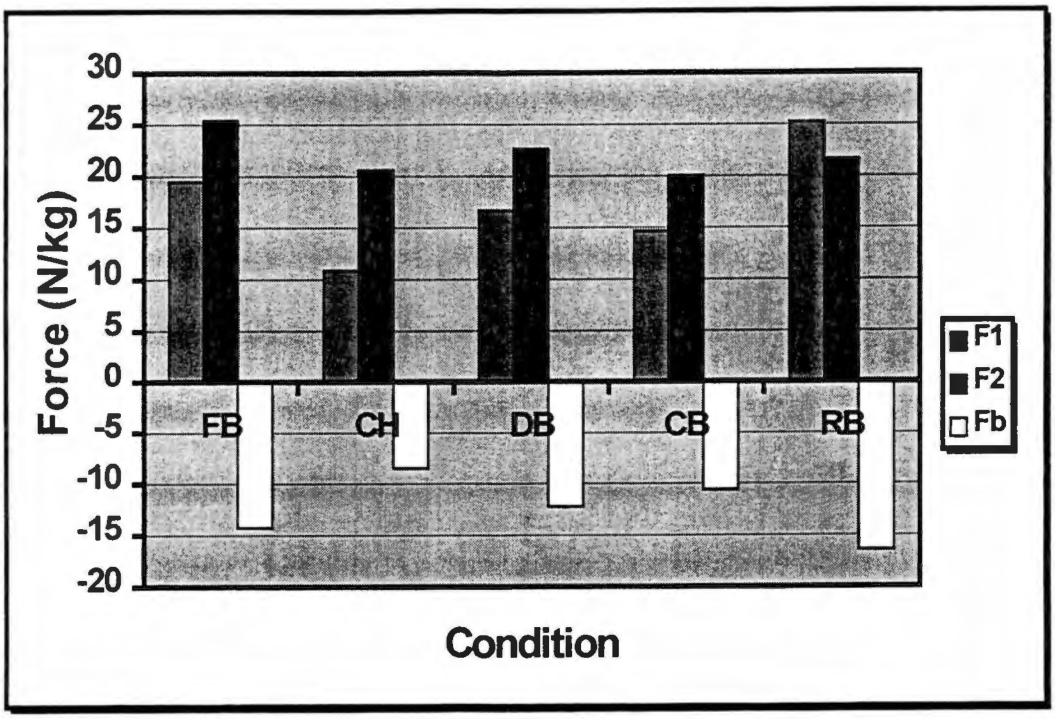

Figure IV.3. Mean peak vertical and braking forces for each condition

Fastball

Individual means and standard deviations for the GRF variables in the FB are presented in Table 11 (Appendix A). ANOVA results demonstrated a significant effect within the FB for F1 (F= 43.88; p= 0.0001), F2 (F= 7.41; p= 0.0008) and F_b (F= 19.74; p= 0.0001). S3 and S1 (30.54 and 28.86 Nkg^{-1}) demonstrated significantly higher vertical forces than S2, S4 and S5 (15.32, 13.66 and 9.11 Nkg^{-1}, respectively). S5 (9.11 Nkg^{-1}) was significantly lower than S3, S1 and S2 (30.54, 28.86 and 15.32 Nkg^{-1}, respectively). The second peak force, F2, was highest for S2 (36.10 Nkg^{-1}) compared to S4, S5, S3 and S1 (24.56, 24.01, 22.20 and 20.33 Nkg^{-1}). F_b was significantly higher for S2, S1 and S3 (-14.60, -16.16 and -16.72 Nkg^{-1}, respectively) compared to S5 and S4 (-11.71 and -12.01 Nkg^{-1}). F2 was larger than F1 for all pitchers except S1 and S3. F_b was larger than F1 for S5.

Change-up

Individual means and standard deviations for the GRF variables in the CH are presented in Table 12 (Appendix A). Comparisons of pitchers within the CH revealed significant differences in F2 (F= 19.84; p= 0.0001) and F_b (F= 83.75; p= 0.0001). Significant differences in F2 were present between S2 (25.51 Nkg^{-1}) compared to S3, S1 and S5 (20.35, 17.99 and 16.67 Nkg^{-1}). S5 (16.69 Nkg^{-1}) was significantly lower that S2, S4 and S3 (25.51, 22.31 and 20.35 Nkg^{-1}). F_b was significantly higher for S1 and S3 (-10.08 and -16.31Nkg^{-1}) compared to S5, S2 and S4 (-6.13, -6.30 and -6.39 Nkg^{-1}). F_b for S3 (-13.31 Nkg^{-1}) was significantly higher than S1 (-10.08 Nkg^{-1}). F2 was larger than F1 for all five pitchers in this condition.

Dropball

Individual means and standard deviations for the GRF variables in the dropball are presented in Table 12 (Appendix A). Comparisons of pitchers within the DB revealed significant differences in F1 (F= 29.19; p= 0.0001), F2 (F= 4.86; p= 0.006) and F_b (F= 63.91; p= 0.0001). F1 for S3 (31.08 Nkg^{-1}) was significantly higher than S2, S1, S4 and S5 (17.35, 15.16, 11.08 and

8.66 Nkg^{1}). F1 for S5 (8.66 Nkg^{-1}) was significantly different than S3 and S2 (31.08 and 17.35 Nkg^{-1}). Significant differences in F2 were present between S2 (28.16 Nkg^{-1}) and S1 and S5 (19.46 and 19.24 Nkg^{-1}). Several differences occurred between the pitchers in maximum braking force. S5 (-7.42 Nkg^{-1}) was significantly lower than S4, S1, S2 and S3 (-9.64, -11.66, -14.95 and -17.25 Nkg^{-1}). In addition, S4 and S1 (-9.64 and -11.66 Nkg^{-1}) were significantly lower than S2 and S3 (-14.95 and -17.25 Nkg^{-1}). Furthermore, S2 (-14.95 Nkg^{-1}) was significantly lower than S3 (-17.25 Nkg^{-1}). F2 was larger than F1 in this condition for all pitchers except S3.

Curveball

Comparisons of pitchers within the CB revealed significant differences in F1 (F= 119.41; p= 0.0001) and F_b (F= 40.40; p= 0.0002). S1 and S5 were the only pitchers in the group that threw a curveball, therefore the comparisons were limited to these two subjects. In both F1 and F_b, S1 (22.44 and -13.38 Nkg^{-1}) was significantly higher than S5 (6.93 and -7.81 Nkg^{-1}). F1 was larger than F2 for S1 however, F2 was larger than F1 for S5. F_b was higher than F1 for S5. Individual means and standard deviations for the GRF variables in the curveball are presented in Table 14 (Appendix A).

Riseball

Individual means and standard deviations for the GRF variables in the fastball are presented in Table 15 (Appendix A). Comparisons of pitchers within the RB revealed significant differences in F1 (F= 27.82; p= 0.0001), F2 (F= 14.83; p= 0.0001) and F_b (F= 133.49; p= 0.0001). The main difference in F1 was present between S5 (6.61 Nkg^{-1}) and S3, S1, S4 and S2 (35.85, 30.68, 27.74, and 25.02 Nkg^{-1}). In addition, S3 (35.85 Nkg^{-1}) was significantly higher than S2 (25.02 Nkg^{-1}). Significant differences in F2 were present between S2 (24.22 Nkg^{-1}) and S4, S3, S5 and S1 (22.08, 21.60, 21.05 and 19.17 Nkg^{-1}). S4 and S3 (22.08 and 21.60 Nkg^{-1}) were also significantly higher than S1 (19.17 Nkg^{-1}). F_b for S5 (-8.87 Nkg^{-1}) was significantly lower than S3, S2, S1 and S4 (-17.75, -17.76, -18.54 and -19.20 Nkg^{-1}). F1 was larger than F2 in all of the pitchers except S5. F_b was larger than F1 for S5.

Kinetics-Group Comparisons

A total of three kinetic variables were examined: F1, F2 and F_b. Participants were placed in the same two groups as previously outlined for kinematic group comparisons. Group 1 (G1) consisted of S1, S4 and S5, where as Group 2 (G2) consisted of S2 and S3. Single factor ANOVAs were performed on each of the three kinetic variables. The initial single factor ANOVA (pitch) compared kinetic variables between pitches for each group. A second ANOVA (groups) was performed to compare differences in force variables between G1 and G2 for each type of pitch. Level of significance for all comparisons was established at $p < 0.05$. Differences between groups within each condition were examined using a Tukey's Post Hoc Comparison ($p < 0.05$). Only those differences that were significant are reported for each pitch.

ANOVA results for G1 demonstrated a significant effect on F1 (F= 5.27; p= 0.001), F2 (F= 5.49; p= 0.0007) and F_b (F= 15.54; p= 0.0001). Significant F1 differences were present between the RB (21.67 Nkg^{-1}), DB (11.63 Nkg^{-1}) and CH (10.41 Nkg^{-1}). FB (22.96 Nkg^{-1}) was significantly higher than both CB (20.04 Nkg^{-1}) and CH (18.99 Nkg^{-1}) for F2. Significant differences occurred in F_b between all the pitches. F_b force in the RB (-15.54 Nkg^{-1}) was significantly higher than CB (-10.60 Nkg^{-1}), DB (-9.57 Nkg^{-1}) and CH (-7.54 Nkg^{-1}). In addition, F_b in the FB was significantly higher than DB and CH.

Comparisons between the different pitches within G2 revealed significant differences in F1 (F= 9.81; p= 0.0001) and F_b (F= 22.86; p= 0.0001). F1 force was significantly lower in the CH (11.60 Nkg^{-1}) compared to RB, DB and FB (30.43, 21.22 and 22.93 Nkg^{-1}, respectively). Furthermore, CH (-9.80 Nkg^{-1}) demonstrated significantly less maximum braking force than FB, DB and RB (-15.66, -16.10 and -17.75 Nkg^{-1}, respectively).

Fastball

ANOVA results demonstrated a significant effect for the FB for F2 ($F= 5.02$; $p= 0.035$) and F_b ($F= 7.71$; $p= 0.010$). G2 (29.15 Nkg^{-1}) demonstrated a significantly higher F2 force compared to G1 (22.97 Nkg^{-1}). G2 (-15.66 N/kg) also demonstrated a significantly higher F_b than G1 (-13.29 Nkg^{-1}).

Change-up

Significant differences in CH were present only for F2 ($F= 9.91$; $p= 0.004$). Similar to the FB, G2 (22.93 Nkg^{-1}) demonstrated a significantly higher F2 force than G1 (18.99 Nkg^{-1}).

Dropball

Comparisons between G1 and G2 for the DB revealed significant differences in F1 ($F= 25.97$; $p= 0.0001$) and F_b ($F= 70.96$; $p= 0.0001$). G2 (24.21 Nkg^{-1}) demonstrated a significantly higher F1 force compared to G1 (11.64 Nkg^{-1}). G2 (-16.10 Nkg^{-1}) also demonstrated a significantly higher F_b than G1 (-9.57 Nkg^{-1}).

Riseball

Comparisons between G1 and G2 for the RB revealed significant differences in F1 ($F= 4.30$; $p= 0.049$) and F2 ($F= 10.37$; $p= 0.003$). G2 (30.43 Nkg^{-1}) demonstrated a significantly higher F1 force compared to G1 (21.68 Nkg^{-1}). G2 (22.90 Nkg^{-1}) also demonstrated a significantly higher F2 force than G1 (20.77 Nkg^{-1}).

CHAPTER V

DISCUSSION

The purpose of this study was to determine the kinematic responses and magnitude of ground reaction forces (GRF) created by the stride leg in selected windmill pitches. The primary focus was on the kinematics of the lower extremity and GRF generated during impact with the ground.

Kinematics

Ball Velocity

Five trials for every pitch and every pitcher were recorded and digitized to obtain ball velocity at the time of release. The release velocity for each pitch was estimated using the ball coordinates obtained through digitization for three consecutive frames following ball release. Due to the limitations of a single camera view, the ball was hidden by the body in some pitches, therefore ball velocities were not estimated for these trials.

Linear velocity was highest in the curveball and fastball compared to the other pitches. The velocity of the fastball ranged from 18.4 $m \cdot s^{-1}$ to 28.6 $m \cdot s^{-1}$. The curveball demonstrated velocities similar to the fastball, however, only two of the five pitchers were able to perform this pitch. The average velocity for the curveball was approximately 0.1 $m{\bullet}s^{-1}$ faster than the fastball. The change-up demonstrated the slowest velocities ranging from 11.7 $m{\bullet}s^{-1}$ to 16.9 $m{\bullet}s^{-1}$, which was significantly different from the curveball and fastball.

The current ball velocities differed somewhat from those reported in previous studies, however certain trends are apparent. Alexander and Haddow's (1982) female pitchers averaged 24.7 $m{\bullet}s^{-1}$ in two trials. The eight female pitchers in Wilson's study (1985) averaged 25.4 $m{\bullet}s^{-1}$ for the fastball and 18.9 $m{\bullet}s^{-1}$ for the change-up. Greene, et al (1994) reported average velocity of 24.7 $m{\bullet}s^{-1}$ for the fastball and 19.2 $m{\bullet}s^{-1}$ for the change-up. In all three studies, the fastball displayed the greatest velocity and the change-up displayed the lowest linear velocity. The method of measuring and calculating ball velocity was not reported in these studies. Therefore, differences observed in the reported values from those in the current study may be related to the particular procedures and calculations utilized.

The greater velocities seen in the fastball may be due to the majority of movement occurring as the wrist flexes to keep the ball moving in a linear path (Greene, 1994). Wrist snap has been identified as a contributing factor for the increase in ball velocity for the fastball. In contrast, lower velocities seen in the change-up may be due to a decrease in wrist snap prior to ball release. The pitchers in this study threw their change-up an average of 6.0 $m{\bullet}s^{-1}$ slower than the fastball, which were similar to the velocity differences reported by in Wilson

(1985), 6.4 $m{\bullet}s^{-1}$ and Greene (1994), 6.7 $m{\bullet}s^{-1}$. The goal of the change-up is to catch the batter off guard by using the same pitching motion as a high velocity pitch, while reducing the speed of the ball by decreasing wrist snap (Wilson, 1985; Greene, et al, 1994).

It is generally acknowledged that the dropball, curveball and riseball are not thrown at a high velocity in order to get adequate movement of the ball, sometimes referred to as "off-speed" pitches. The linear velocity for the dropball, curveball and riseball in the present study averaged 19.6, 20.4 and 19.8 $m{\bullet}s^{-1}$, respectively. These velocities differ from the average velocities reported by Wilson (1985), 24.5, 23.3 and 23.5 $m{\bullet}s^{-1}$, respectively. The velocities of the curveball and riseball were slightly lower than the velocities reported by Greene, et al (1994), 23.4 and 24.6 $m{\bullet}s^{-1}$. These differences may be again attributed to the method of ball velocity estimation as mentioned previously.

Stride Length

Stride length is a major factor influencing the velocity of the ball at release and may also effect the amount of distraction force that occurs at the shoulder (Hay, 1973; Zollinger, 1973; Wilson, 1985; Werner et al, in press). Werner et al., (in press) contends that utilizing a longer stride, such as 80-100 percent of the pitcher's height, may serve to reduce these stresses. Furthermore, a longer stride provides an advantage to the pitcher because it creates a shorter distance over which the ball needs to travel (Hay, 1973; Werner, et al, in press).

Hay (1973) states that stride length serves two important roles in pitching. The stride places the body in a position where the hip and trunk rotation muscles can contribute to the velocity of the ball at release. In addition, the rotation of the body into an "open" position results in an increased distance through which the ball may be accelerated.

The pitchers in this study achieved an average stride length of 71% of their body height. Zollinger (1973) reported that an average stride length was 69% of shoulder height. The two female pitchers examined by Alexander and Haddow (1982) averaged 65% of shoulder height, whereas Wilson (1985) reported an average stride length of the Australian pitchers as 76% and New Zealand pitchers as 95% of shoulder height.

Stride lengths are indicative of different strategies used for different pitches. The findings in this study demonstrated that the stride length was the longest in the riseball (138.97 cm) and shortest in the change-up (113.80 cm). The riseball had the longest stride length because greater flexion of the rear knee was necessary in order to lower the release point of the pitch. The lower release point is critical for producing backspin for proper lift of the ball (Greene et al., 1994). In contrast, the change-up had the shortest stride length. To assist in the decreased final release velocity of the ball, the forward momentum is decreased which reduces the overall length of the stride (Greene et al., 1994). This, in turn, may be associated with the low braking force (F_b) observed in the change-up. In addition, the fastball (134.33cm), curveball (123.46 cm) and dropball (120.13 cm) all exhibited a decrease in stride length as compared to the riseball. This is most likely due to the fact that the delivery was more forward and upright for these pitches.

Joint Kinematics

Lower extremity angles were measured in the stride leg throughout the pitching motion for the hip, knee and ankle. Specific events of interest were the angles at the point of contact with the ground (JAC), maximum angle achieved (MAX) and minimum angle achieved (MIN) during each pitch. The pitchers were divided into two groups for further analysis. Overall, there were no major differences between G1 and G2 for the hip or knee kinematic variables. There were several differences in the position of the ankle between the two groups, most notably in the riseball.

Joint angle at contact (JAC) was defined as the angle of the joint as the foot contacted the ground. Stride length and joint contact angle for the hip, knee and ankle in each condition are found in Table V.1. The fastball (23.02°) had the largest hip angle at the point of contact, however the difference between the fastball and riseball was minimal (1.60°). The change-up (14.89°) had the smallest hip angle upon contact with the ground and was significantly smaller than the fastball. The smaller angle seen in the change up may be due to the more upright body position because this pitch does not require an exaggerated stride. The same pattern occurred in the group comparisons. The fastball (G1= 22.52°; G2= 23.77°) had the largest hip angle at contact and the change-up (G1= 16.05°; G2= 13.15°) had the smallest hip angle. G2 averaged larger hip angles than G1, however these differences were not significant.

Table V.1. Stride Length and Joint Angle at Contact.

Pitch	Stride Length (cm)	Hip (deg)	Knee (deg)	Ankle (deg)	Hip/Knee/Ankle (deg)
FB	134.33	23.02	8.96	-9.22	22.76
CH	113.80	14.89	6.53	-15.02	6.40
DB	120.13	20.12	8.34	-13.24	15.22
CB	123.46	23.02	11.33	-5.88	28.47
RB	138.97	21.42	8.91	-6.28	24.05

The knee angle at contact was greatest in the curveball (11.33°), closely followed by the fastball (8.96°) and riseball (8.91°). The smallest angle of knee flexion occurred in the change-up (6.53°). In the group comparisons, the largest knee angle at contact occurred in the curve in G1 (11.33°) and in the riseball in G2 (8.26°). The smallest knee angles at contact occurred in the change-up in G1 (5.99°) and in the dropball in G2 (7.20°). Werner, et al (in press) state that the angle of the knee should be flexed approximately 30° when the foot contacts the ground. A knee angle greater than 30° of flexion may result in additional stress on the shoulder and jeopardize ball speed. The knee angle for the pitchers in the present study did not exceed 30° in any of the pitches.

Finally, the ankle was in a plantarflexed position in all five pitches upon contact with the ground. The ankle was more plantarflexed in the change-up (-15.02°) and least plantarflexed (more dorsiflexed) in the curveball (-5.88°) and riseball (-6.28°). In all five pitches, S1 landed in dorsiflexion, which suggests she used a slightly different strategy than the other four pitchers in the delivery of the different pitches. Both G1 and G2 contacted the ground with more dorsiflexion in the riseball (G1= -2.17°; G2= 12.44°) and more plantarflexion in the change-up (G1= -12.60°; G2= -18.66°). In general, all of the pitchers demonstrated a common style represented by slight flexion at the hip and knee, with the ankle being in a more plantarflexed position.

Comparison of stride lengths to total combined posture at contact indicate that longer stride lengths are associated with a less upright position of the body (Table V.1). In general the fastball, curveball and riseball had longer stride lengths and more flexed body position. In contrast, the body assumed a more upright position in pitches with a shorter stride length, such as the change-up and dropball. The results also indicated trends of slower ball velocities with a more upright body position.

Wilson (1985) measured the hip, knee and ankle angles at the time of ball release. The hip angle was largest in the dropball and smallest in the change-up. The angle of the knee at ball release was largest in the curveball and smallest in the riseball. The ankle was more dorsiflexed at ball release for the fastball, dropball and curveball. Plantarflexion was demonstrated in the change-up and riseball. The purpose of this study was to investigate the kinematic responses at the point of contact with the ground. Ball release in the present study occurred approximately 267 ms after contact with the ground, therefore differences in the joint angles may be due to the difference in time between contact and ball release.

Maximum angle achieved is defined as the largest angle achieved during the pitching motion at each joint. The hip reached the highest maximum angle in both the fastball and curveball. There was more variation in the hip angle in the fastball (11.26°-35.04°) compared to the curveball (20.09°-27.37°). The larger variation in the fastball may be due to the higher number of pitchers examined in the fastball condition (5 pitchers) compared to the curveball condition (2 pitchers), which would be representative of individual pitching styles. The knee and ankle reached the largest maximum angle in the change-up (21.04° and 8.85° DF, respectively). Maximum knee and ankle angles in the change-up occurred later in the pitch, near ball release, compared to the other pitches (150 and 130 ms, respectively). The change-up also showed the shortest stride length, which contributes to the decreased final velocity of the ball at release. The fastball and curveball had the smallest maximum angle in the knee (14.98° and 15.92°, respectively). The dropball and fastball had the smallest maximum angle for the ankle (2.18° and 3.02° of dorsiflexion, respectively), whereas the change-up had the smallest maximum hip angle (15.44°).

Kinetics

Two vertical peaks of GRF and a maximum braking force characterize the windmill pitch. The stride leg created the forces as it contacted the ground. Three primary kinetics variables were examined, first peak force (F1), second peak force (F2) and maximum braking force (F_b). F1 is defined as the first maximum force of vertical GRF after the foot contacts the ground. F2 is defined as the second maximum force of vertical GRF after the foot contacted the ground. Fb is defined as the maximum braking force of the anterior-posterior GRF that occurred after the foot contacts the ground. GRF was normalized by subject's body mass, however body weight was partially supported by the push (rear) leg during the contact. Therefore, it is possible that GRF experienced in the stride leg should be higher at contact than reported in the present study.

In addition, similarities were found in kinematic and kinetic variables for G2. There were significant differences in the variables between the two groups for each pitch condition. Overall, G2 had higher GRF values in F1, F2, and F_b in the fastball, change-up, dropball and riseball.

The riseball demonstrated the highest average F1 (2.60 BW) followed by the fastball (2.00 BW), whereas the change-up produced the lowest F1 (1.10 BW). The second peak vertical force was highest in the fastball (2.60 BW) followed by the dropball (2.30 BW) and change-up (2.10 BW). The smallest F2 occurred in the curveball (2.01). For the group of five pitchers, demonstrated a larger F2 than F1 in all pitches but the riseball.

The results of the GRF analysis indicated that the body experienced low to moderate impact forces during the typical pitches. Running is typically used as the standard reference for sport activities (McClay, et al, 1994). Peak vertical GRF during distance running are approximately 2.20 – 2.80 BW (Cavanagh & Lafortune, 1980). Peak GRFs produced in walking, ranging 1.00 - 1.20 BW, are lower than in running (Hamill & Knutzen, 1995). In this study, the peak vertical forces (F1 and F2) experienced during pitching ranged from 1.10 – 2.60 BW among the pitchers. The force values are similar to those reported in running and higher than those reported in walking.

In comparison to force studies on other activities, the average second maximum forces (F2) for the fastball (2.60 BW), dropball (2.30 BW), riseball (2.20 BW), and change-up (2.10 BW) were comparable to the average peak force produced in high impact aerobic manuevers (2.12 – 2.88 BW) (Ricard & Veatch, 1990). They were higher than the average peak forces produced in low impact aerobic manuevers (1.52 – 1.67 BW). F1 and F2 produced in pitching, however, were smaller than those reported in other sport specific skills, such as cutting, jumpshot and lay-up landings in basketball and blocking and spiking in volleyball (McClay, 1994; Adrian & Laughlin, 1983). Again, the peak GRFs should be higher due the double support at the time of contact.

Maximum braking forces for the pitches (0.90 - 1.70 BW) were higher than those typically reported for running (0.45 BW) and walking (0.15 BW) (Cavanagh & Lafortune, 1980; Hamill & Knutzen, 1995). In addition, the braking forces produced were higher than common movements performed in basketball, with the exception of landing after a layup shot (2.50 BW)

(McClay, et al, 1994). The riseball demonstrated the highest braking force (1.70 BW) followed by the fastball (1.40 BW). The lowest braking force occurred in the change-up (0.90 BW). These findings indicate a trend that pitches with the highest F1 values are accompanied by high maximum braking forces and vice versa for pitchers with the lowest F1 values. Olson and Hunter (1987) stated that forward momentum is created by the throwing arm and push leg as the stride leg contacts the ground. The momentum that is created by the pitching arm and push leg is absorbed in a short period of time through the eccentric contraction of the quadriceps muscles of the stride leg. The absorption of the momentum contributes to the high braking force. A higher braking force may increase shear stress placed on the lower extremity joints, which may be detrimental to the integrity of the lower extremity.

Individually, the highest F1 value was obtained by subject 2 (3.68 BW) in the fastball. Subject 5 recorded the lowest F1 value (0.67 BW) which occurred in the riseball. F1 values ranged 0.92 - 3.11 BW in the fastball, 0.88 - 1.34 BW in the change-up, 0.88 - 3.10 BW in the dropball, and 0.67 - 3.65 BW in the riseball.

Subject 3 demonstrated the highest braking force in the fastball, change-up and dropball (1.70, 1.36, 1.76 BW, respectively). In addition, Subject 3 demonstrated a high braking force in the riseball (1.81 BW). Subject 5 demonstrated very low braking forces across each pitch compared to the other pitchers. Braking forces for Subject 5 were below 1 BW except for the fastball (1.19 BW). A breakdown of individual and group ground reaction forces in the vertical and antero-posterior component can be found in Table 16 (Appendix A).

The riseball demonstrated the highest F1 and F_b values as well as the longest stride length. In contrast, the change-up exhibited the lowest F1 and F_b, the shortest stride length, more erect stance and the slowest ball velocity. In addition, the change up had the smallest hip and knee angles and landed in more plantarflexion at contact.

Summary

Stride lengths of the participants in this study indicate that different strategies were used in the delivery of the various pitches. Stride lengths were longest for the riseball and shortest for the change-up. In general, the pitchers adopted a style characterized by extended hip and knee joint and plantarflexed ankle joint.

Comparison of stride lengths to total body range of motion at contact indicated that longer stride lengths are associated with a less upright position of the body. In general the fastball, curveball and riseball had longer stride lengths and greater total body range of motion. In contrast, the body assumes a more upright position in pitches with a shorter stride length, such as the change-up and dropball. The results also indicated trends of slower ball velocities with a more upright body position.

Peak vertical forces during pitching are higher than those reported in walking and low impact aerobics. In addition, peak vertical forces experienced during pitching appear to be similar to those reported in distance running and high impact aerobics. However, peak forces are lower than those reported in jump/landing skills in basketball and volleyball.

Maximum braking forces of pitching are higher than those reported in running and walking. In addition, the braking forces produced in pitching are higher than common movements performed in basketball, with the exception of landing after a layup shot. The riseball had the highest braking force followed by the fastball, whereas the lowest braking force occured in the change-up. The findings indicate a trend that pitches with the highest F1 values are accompanied by high maximum braking forces and vice versa for pitchers with the lowest F1 values. These findings indicate trends that the pitches with the highest F1 values are accompanied by high maximum braking forces and vice versa for pitchers with the lowest F1 values.

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APPENDICES

APPENDIX A - TABLES

Table 1. Descriptive and Physical Characteristics of the Subjects

	AGE (Yr)	HT (m)	WT (kg)	TOTAL EXPERIENCE (Yr)	COLLEGE EXPERIENCE (Yr)
S1	27	1.79	76.14	12	5
S2	20	1.82	67.77	11	3
S3	21	1.87	82.34	13	3
S4	26	1.71	57.45	20	4
S5	19	1.58	62.57	7	1
Group	**22.5 (± 3.65)**	**1.76 (± 0.11)**	**68.99 (± 9.63)**	**12.6 (± 4.72)**	**3.2 (± 1.48)**

Table 2. Stride Length Characteristics of the Individual Subjects (cm)

	FB	CH	DB	CB	RB
S1	134.4	126.16	104	116.33	128.6
S2	133.2	108.23	126.73	---	148.6
S3	139.13	125.9	135.03	---	147.46
S4	124.3	69.53	105.5	---	138.8
S5	140.6	139.2	129.4	130.6	131.4
Group	**134.33 (± 6.41)**	**113.80 (± 27.09)**	**120.13 (± 14.37)**	**123.46 (± 7.14)**	**138.97 (±9.08)**

Table 3. Means and Standard Deviations for Ball Velocity (m/s)

	FB	CH	DB	CB	RB
S1	21.38 (± 4.06)	15.83 (± 0.74)	20.50 (± 1.20)	21.83 (± 5.05)	18.01 (± 0.47)
S2	19.49 (± 0.86)	12.72 (± 0.93)	19.72 (± 0.38)	--- ---	19.20 (± 0.65)
S3	21.85 (± 0.74)	14.53 (± 0.28)	21.54 (± 0.79)	--- ---	22.73 (± 0.82)
S4	19.26 (± 0.49)	14.34 (± 1.13)	18.87 (± 0.17)	--- ---	19.39 (± 0.47)
S5	20.13 (± 0.39)	14.79 (± 0.43)	17.99 (± 0.67)	19.15 (± 0.34)	19.64 (± 0.30)
Group	**20.35 (± 2.04)**	**14.44 (± 1.24)**	**19.66 (± 1.43)**	**20.49 (± 3.66)**	**19.79 (± 1.69)**

Table 4. Kinematic Variables of Hip, Knee and Ankle: All Conditions

HIP

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
FB	23.02 (±11.93)	23.15 (±11.89)	40.00 (±40.00)	17.97 (±4.29)	12.00 (±40.00)
CH	14.89 (±4.08)	15.44 (±3.79)	60.00 (±60.00)	12.64 (±2.23)	100.00 (±60.00)
DB	20.12 (±5.23)	21.38 (±4.51)	70.00 (±50.00)	18.40 (±4.32)	80.00 (±60.00)
CB	23.02 (±4.52)	23.73 (±3.64)	60.00 (±60.00)	21.09 (±3.45)	100.00 (±60.00)
RB	21.42 (±10.94)	21.98 (±10.72)	40.00 (±40.00)	17.46 (±5.68)	120.00 (±40.00)

Table 4a

KNEE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
FB	8.96 (±2.88)	14.98 (±3.18)	110.00 (±20.00)	8.71 (±2.83)	40.00 (±50.00)
CH	6.53 (±3.01)	21.04 (±7.10)	150.00 (±10.00)	6.53 (±3.01)	20.00 (± 0.00)
DB	8.34 (±3.28)	16.05 (±3.91)	120.00 (±20.00)	8.15 (±3.44)	20.00 (±30.00)
CB	11.33 (±1.56)	15.92 (±1.78)	120.00 (±30.00)	11.23 (±1.53)	30.00 (±40.00)
RB	8.91 (±4.62)	17.05 (±4.29)	130.00 (±20.00)	8.91 (±4.62)	20.00 (±0.00)

Table 4b

ANKLE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
FB	-9.22 (±12.49)	3.02 (±7.20)	10.00 (±50.00)	-11.88 (±8.32)	40.00 (±50.00)
CH	-15.02 (±15.24)	8.85 (±6.03)	130.00 (±60.00)	-18.02 (±9.98)	40.00 (±40.00)
DB	-13.24 (±12.15)	2.18 (±5.54)	110.00 (±50.00)	-16.16 (±7.85)	50.00 (±60.00)
CB	-5.88 (±13.85)	8.35 (±2.36)	80.00 (±70.00)	-11.28 (±8.57)	80.00 (±70.00)
RB	-6.28 (±9.77)	3.17 (±5.94)	90.00 (±50.00)	-8.73 (±6.70)	40.00 (±40.00)

Table 4c

Table 5. Kinematic Variables for Hip, Knee and Ankle: Fastball

HIP

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	27.31 (± 1.06)	27.31 (± 1.06)	17.00 (± 0.00)	20.98 (± 2.74)	140.00 (± 10.00)
S2	33.14 (± 24.09)	33.16 (± 24.08)	50.00 (± 46.00)	22.18 (± 2.37)	117.00 (± 40.00)
S3	14.41 (± 1.43)	14.43 (± 1.45)	27.00 (± 15.00)	11.44 (± 1.61)	120.00 (± 10.00)
S4	19.20 (± 1.31)	19.83 (± 1.19)	70.00 (± 52.00)	18.81 (± 1.33)	80.00 (± 50.00)
S5	21.04 (± 1.37)	21.04 (± 1.37)	17.00 (± 0.00)	16.44 (± 1.48)	140.00 (± 10.00)
Group	**23.02 (± 11.93)**	**23.15 (± 11.89)**	**36.00 (± 36.00)**	**17.97 (± 4.29)**	**119.00 (± 36.00)**

Table 5a

KNEE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	11.87 (± 1.37)	15.52 (± 0.73)	113.00 (± 22.00)	11.87 (± 1.37)	17.00 (± 0.00)
S2	10.01 (± 2.95)	18.11 (± 1.83)	127.00 (± 10.00)	10.01 (± 2.95)	17.00 (± 0.00)
S3	5.68 (± 2.19)	14.15 (± 3.55)	113.00 (± 10.00)	5.68 (± 2.19)	17.00 (± 0.00)
S4	7.68 (± 2.07)	16.57 (± 1.33)	133.00 (± 0.00)	7.68 (± 2.07)	17.00 (± 0.00)
S5	9.58 (± 1.41)	10.54 (± 1.14)	80.00 (± 10.00)	8.29 (± 0.81)	117.00 (± 56.00)
Group	**8.96 (± 2.88)**	**14.98 (± 3.18)**	**113.00 (± 23.00)**	**8.71 (± 2.83°)**	**37.00 (± 47.00)**

Table 5b

ANKLE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	6.46 (± 1.20)	6.46 (± 1.20)	17.00 (± 0.00)	-3.22 (± 1.38)	123.00 (± 10.00)
S2	-19.25 (± 5.18)	0.75 (± 2.15)	133.00 (± 0.00)	-19.25 (± 5.18)	17.00 (± 0.00)
S3	-9.78 (± 1.54)	-2.28 (± 1.37)	120.00 (± 10.00)	-9.78 (± 1.54)	17.00 (± 0.00)
S4	-15.03 (± 9.09)	-2.08 (± 2.24)	133.00 (± 0.00)	-15.32 (± 8.63)	23.00 (± 15.00)
S5	-8.50 (± 18.61)	12.27 (± 10.10)	103.00 (± 22.00)	-11.82 (± 11.32)	40.00 (± 52.00)
Group	**-9.22 (± 12.49)**	**3.02 (± 7.20)**	**101.00 (± 46.00)**	**-11.88 (± 8.32)**	**44.00 (± 47.00)**

Table 5c

Table 6. Kinematic Variables for Hip, Knee and Ankle: Change-Up

HIP

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	22.39 (± 1.56)	22.39 (± 1.56)	17.00 (± 0.00)	15.99 (± 1.80)	163 (± 14)
S2	14.29 (± 1.55)	14.62 (± 1.43)	96.00 (± 74.00)	12.98 (± 1.80)	83 (± 47)
S3	12.01 (± 1.13)	14.03 (± 0.99)	113.00 (± 18.00)	11.83 (± 0.99)	43 (± 60)
S4	12.77 (± 0.80)	13.15 (± 1.02)	60.00 (± 60.00)	11.66 (± 0.71)	117 (± 62)
S5	12.99 (± 1.29)	12.99 (± 1.29)	17.00 (± 0.00)	10.72 (± 1.02)	93 (± 91)
Group	**14.89 (± 4.08)**	**15.44 (± 3.79)**	**61.00 (± 57.00)**	**12.64 (± 2.23)**	**100.00 (± 58.00)**

Table 6a

KNEE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	5.76 (± 3.88)	15.36 (± 3.55)	163.00 (± 14.00)	5.76 (± 3.87)	17.00 (± 0.00)
S2	10.04 (± 1.74)	28.03 (± 2.78)	160.00 (± 9.00)	10.04 (± 1.74)	17.00 (± 0.00)
S3	4.63 (± 2.87)	22.86 (± 10.45)	140.00 (± 9.00)	4.63 (± 2.87)	17.00 (± 0.00)
S4	6.28 (± 2.52)	14.72 (± 0.55)	157.00 (± 15.00)	6.28 (± 2.52)	17.00 (± 0.00)
S5	5.94 (± 0.83)	24.22 (± 2.14)	147.00 (± 7.00)	5.94 (± 0.83)	17.00 (± 0.00)
Group	**6.53 (± 3.01)**	**21.04 (± 7.10)**	**153.00 (± 14.00)**	**6.53 (± 3.01)**	**17.00 (± 0.00)**

Table 6b

ANKLE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	12.35 (± 1.30)	12.35 (± 1.30)	17.00 (± 0.00)	-2.64 (± 2.71)	123.00 (± 9.00)
S2	-23.24 (± 8.18)	10.91 (± 3.66)	160.00 (± 9.00)	-23.24 (± 8.18)	17.00 (± 0.00)
S3	-14.08 (± 2.19)	4.89 (± 11.27)	140.00 (± 9.00)	-14.08 (± 2.19)	17.00 (± 0.00)
S4	-28.05 (± 3.24)	4.52 (± 1.44)	163.00 (± 7.00)	-28.05 (± 3.24)	17.00 (± 0.00)
S5	-22.10 (± 3.48)	11.59 (± 0.89)	147.00 (± 7.00)	-22.10 (± 3.48)	17.00 (± 0.00)
Group	**-15.02 (± 15.24)**	**8.85 (± 6.03)**	**125.00 (± 57.00)**	**-18.02 (± 9.98)**	**38.00 (± 44.00)**

Table 6c

Table 7. Kinematic Variables for Hip, Knee and Ankle: Dropball

HIP

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	26.71 (± 1.17)	26.74 (± 1.17)	37.00 (± 44.00)	21.46 (± 3.14)	160.00 (± 9.00)
S2	24.36 (± 1.36)	24.60 (± 1.17)	30.00 (± 30.00)	22.71 (± 0.50)	110.00 (± 52.00)
S3	13.30 (± 2.11)	14.29 (± 1.55)	50.00 (± 33.00)	11.83 (± 1.38)	100.00 (± 48.00)
S4	17.16 (± 1.82)	20.17 (± 0.96)	123.00 (± 9.00)	17.09 (± 1.75)	23.00 (± 9.00)
S5	19.08 (± 2.39)	21.09 (± 1.57)	123.00 (± 9.00)	18.92 (± 2.33)	30.00 (± 14.00)
Group	**20.12 (± 5.23)**	**21.38 (± 4.51)**	**73.00 (± 50.00)**	**18.40 (± 4.32)**	**85.00 (± 60.00)**

Table 7a

KNEE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	8.47 (± 1.21)	11.49 (± 2.66)	97.00 (± 30.00)	7.51 (± 2.69)	47.00 (± 67.00)
S2	10.26 (± 1.59)	17.71 (± 2.09)	113.00 (± 14.00)	10.26 (± 1.59)	17.00 (± 0.00)
S3	4.14 (± 1.25)	13.35 (± 2.54)	117.00 (± 12.00)	4.14 (± 1.25)	17.00 (± 0.00)
S4	6.27 1.95)	16.76 (± 1.53)	140.00 (± 15.00)	6.27 (± 1.95)	17.00 (± 0.00)
S5	12.56 (± 0.99)	20.96 (± 1.42)	123.00 (± 9.00)	12.56 (± 0.99)	17.00 (± 0.00)
Group	**8.34 (± 3.28)**	**16.05 (± 3.91)**	**118.00 (± 21.00)**	**8.15 (± 3.44)**	**22.00 (± 30.00)**

Table 7b

ANKLE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	6.72 (± 1.46)	6.72 (± 1.46)	17.00 (± 0.00)	-7.86 (± 1.08)	160.00 (± 9.00)
S2	-17.55 (± 1.75)	-0.76 (± 3.19)	133.00 (± 0.00)	-17.55 (± 1.75)	17.00 (± 0.00)
S3	-11.43 (± 1.30)	-4.64 (± 1.26)	120.00 (± 7.00)	-11.43 (± 1.30)	17.00 (± 0.00)
S4	-27.93 (± 7.25)	0.18 (± 2.00)	147.00 (± 7.00)	-27.93 (± 7.25)	17.00 (± 0.00)
S5	-16.02 (± 4.67)	9.42 (± 1.01)	123.00 (± 9.00)	-16.02 (± 4.67)	17.00 (± 0.00)
Group	**-13.24 (± 12.15)**	**2.18 (± 5.54)**	**108.00 (± 48.00)**	**-16.16 (± 7.85)**	**45.00 (± 59.00)**

Table 7c

Table 8. Kinematic Variables for Hip, Knee and Ankle: Curveball

HIP		JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
	S1	26.70 (± 1.95)	26.73 (± 1.91)	33.00 (± 37.00)	23.97 (± 0.93)	123.00 (± 43.00)
	S5	19.34 (± 2.88)	20.73 (± 1.90)	90.00 (± 68.00)	18.21 (± 2.15)	77.00 (± 60.00)
	Group	**23.02 (± 4.52)**	**23.73 (± 3.64)**	**62.00 (± 60.00)**	**21.09 (± 3.42)**	**100.00 (± 55.00)**

Table 8a

KNEE		JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
	S1	11.85 (± 1.60)	16.78 (± 1.33)	120.00 (± 14.00)	11.85 (± 1.80)	17.00 (± 0.00)
	S5	10.80 (± 1.26)	15.06 (± 1.87)	117.00 (± 37.00)	10.60 (± 1.04)	40.00 (± 52.00)
	Group	**11.33 (± 1.56)**	**15.92 (± 1.78)**	**118.00 (± 27.00)**	**11.23 (± 1.53)**	**28.00 (± 37.00)**

Table 8b

ANKLE		JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
	S1	6.63 (± 1.45)	6.63 (± 1.45)	17.00 (± 0.00)	-4.16 (± 0.62)	140.00 (± 15.00)
	S5	-18.40 (± 6.18)	10.07 (± 1.75)	140.00 (± 25.00)	-18.40 (± 6.18)	17.00 (± 0.00)
	Group	**-5.88 (± 13.85)**	**8.35 (± 2.36)**	**78.00 (± 67.00)**	**-11.28 (± 8.57)**	**78.00 (± 66.00)**

Table 8c

Table 9. Kinematic Variables for Hip, Knee and Ankle: Riseball

HIP

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	26.61 (± 1.52)	26.74 (± 1.39)	30.00 (± 30.00)	23.30 (± 1.85)	147.00 (± 7.00)
S2	32.60 (± 19.52)	33.18 (± 19.16)	40.00 (± 52.00)	23.96 (± 2.85)	100.00 (± 49.00)
S3	13.32 (± 1.09)	13.78 (± 1.41)	40.00 (± 32.00)	10.99 (± 1.39)	120.00 (± 7.00)
S4	17.92 (± 3.28)	19.38 (± 0.74)	37.00 (± 44.00)	15.51 (± 2.52)	110.00 (± 52.00)
S5	16.67 (± 2.76)	16.82 (± 2.68)	43.00 (± 60.00)	13.51 (± 1.35)	120.00 (± 41.00)
Group	**21.42 (± 10.94)**	**21.98 (± 10.72)**	**38.00 (± 42.00)**	**17.46 (± 5.68)**	**119.00 (± 37.00)**

Table 9a

KNEE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	14.38 (± 0.93)	22.51 (± 2.16)	143.00 (± 9.00)	14.38 (± 0.93)	17.00 (± 0.00)
S2	12.30 (± 3.80)	20.68 (± 2.30)	120.00 (± 14.00)	12.30 (± 3.80)	17.00 (± 0.00)
S3	4.22 (± 0.94)	14.54 (± 1.24)	113.00 (± 7.00)	4.22 (± 0.94)	17.00 (± 0.00)
S4	4.67 (± 2.94)	13.71 (± 2.14)	130.00 (± 7.00)	4.67 (± 2.94)	17.00 (± 0.00)
S5	8.97 (± 1.34)	13.79 (± 2.32)	127.00 (± 35.00)	.97 (± 1.34)	17.00 (± 0.00)
Group	**8.91 (± 4.62)**	**17.05 (± 4.29)**	**127.00 (± 19.00)**	**8.91 (± 4.62)**	**17.00 (± 0.00)**

Table 9b

ANKLE

	JAC (deg)	MAX (deg)	TMAX (ms)	MIN (deg)	TMIN (ms)
S1	7.61 (± 2.46)	7.61 (± 2.46)	17.00 (± 0.00)	-2.79 (± 0.58)	93.00 (± 19.00)
S2	-14.47 (± 4.38)	-1.53 (± 1.76)	123.00 (± 15.00)	-14.47 (± 4.38)	17.00 (± 0.00)
S3	-10.42 (± 0.49)	-3.07 (± 0.74)	120.00 (± 7.00)	-10.42 (± 0.49)	17.00 (± 0.00)
S4	0.02 (± 3.53)	1.50 (± 2.72)	63.00 (± 63.00)	-1.81 (± 1.49)	60.00 (± 34.00)
S5	-14.14 (± 7.88)	11.33 (± 2.60)	130.00 (± 21.00)	-14.14 (± 7.88)	17.00 (± 0.00)
Group	**-6.28 (± 9.77)**	**3.17 (± 5.94)**	**91.00 (± 53.00)**	**-8.73 (± 6.70)**	**41.00 (± 36.00)**

Table 9c

Table 10. Means and Standard Deviations for GRF Variables

	F1 (N/kg)	T1 (ms)	F2 (N/kg)	T2 (ms)	F_b (N/kg)	TF_b (ms)
FB	19.50 (±9.25)	18.00 (±4.00)	25.44 (±7.31)	62.00 (±17.00)	-14.24 (±2.36)	34.00 (±10.00)
CH	10.89 (±3.24)	16.00 (±5.00)	20.57 (±3.58)	71.00 (±24.00)	-8.44 (±2.99)	55.00 (±21.00)
DB	16.67 (±8.64)	19.00 (±4.00)	22.60 (±4.95)	69.00 (±21.00)	-12.19 (±3.76)	41.00 (±17.00)
CB	14.68 (±8.45)	19.00 (±1.00)	20.04 (±1.28)	73.00 (±16.00)	-10.60 (±3.21)	48.00 (±25.00)
RB	25.18 (±11.03)	18.00 (±3.00)	21.62 (±1.92)	69.00 (±16.00)	-16.43 (±3.97)	32.00 (±18.00)

Table11. Individual Means and Standard Deviations: GRF Variables

FASTBALL

	F1 (N/kg)	T1 (ms)	F2 (N/kg)	T2 (ms)	F_b (N/kg)	TF_b (ms)
S1	28.86 (±1.04)	16.00 (±2.00)	20.33 (±.65)	66.00 (±2.00)	-16.16 (±1.73)	22.00 (±2.00)
S2	15.32 (±2.92)	12.00 (±8.00)	36.10 (±10.95)	42.00 (±8.00)	-14.60 (±1.14)	34.00 (±2.00)
S3	30.54 (±5.60)	20.00 (±0.00)	22.20 (±1.47)	83.00 (±9.00)	-16.72 (±1.21)	25.00 (±4.00)
S4	13.66 (±2.33)	20.00 (±0.00)	24.56 (±1.97)	61.00 (±15.00)	-12.01 (±0.70)	37.00 (±3.00)
S5	9.11 (±2.47)	20.00 (±0.00)	24.01 (±1.65)	57.00 (±16.00)	-11.71 (±0.71)	46.00 (±7.00)

Table 12. Individual Means and Standard Deviations: GRF Variables

CHANGE-UP

	F1 (N/kg)	T1 (ms)	F2 (N/kg)	T2 (ms)	F_b (N/kg)	TF_b (ms)
S1	12.56 (±0.69)	13.00 (±1.00)	17.99 (±1.81)	55.00 (±15.00)	-10.08 (±0.66)	43.00 (±6.00)
S2	10.04 (±0.89)	8.00 (±1.00)	25.51 (±2.57)	50.00 (±4.00)	-6.30 (±0.48)	75.00 (±10.00)
S3	13.16 (±6.53)	20.00 (±0.00)	20.35 (±1.15)	71.00 (±19.00)	-13.31 (±1.43)	34.00 (±5.00)
S4	8.70 (±0.64)	20.00 (±0.00)	22.31 (±1.69)	81.00 (±11.00)	-6.39 (±0.36)	74.00 (±9.00)
S5	9.97 (±0.84)	18.00 (±3.00)	16.69 (±1.23)	97.00 (±27.00)	-6.13 (±0.44)	47.00 (±28.00)

Table 13. Individual Means and Standard Deviations: GRF Variables

DROPBALL

	F1 (N/kg)	T1 (ms)	F2 (N/kg)	T2 (ms)	F_b (N/kg)	TF_b (ms)
S1	15.16 (±3.84)	20.00 (±1.00)	19.46 (±.77)	90.00 (±12.00)	-11.66 (±1.23)	30.00 (±4.00)
S2	17.35 (±2.97)	17.00 (±6.00)	28.16 (±8.14)	47.00 (±6.00)	-14.95 (±1.17)	33.00 (±2.00)
S3	31.08 (±6.04)	20.00 (±0.00)	21.43 (±0.72)	75.00 (±5.00)	-17.25 (±0.94)	23.00 (±5.00)
S4	11.08 (±0.90)	20.00 (±0.00)	24.70 (±2.49)	52.00 (±.3.00)	-9.64 (±0.43)	54.00 (±3.00)
S5	8.66 (±2.55)	16.00 (±5.00)	19.24 (±0.94)	80.00 (±26.00)	-7.42 (±0.76)	65.00 (±6.00)

Table 14. Individual Means and Standard Deviations: GRF Variables

CURVEBALL

	F1 (N/kg)	T1 (ms)	F2 (N/kg)	T2 (ms)	F_b (N/kg)	TF_b (ms)
S1	22.44 (±3.00)	18.00 (±2.00)	20.04 (±.67)	80.00 (±16.00)	-13.38 (±1.60)	26.00 (±2.00)
S5	6.93 (±1.03)	19.00 (±1.00)	20.05 (±1.80)	66.00 (±15.00)	-7.81 (±1.30)	70.00 (±13.00)

Table 15. Individual Means and Standard Deviations: GRF Variables

RISEBALL

	F1 (N/kg)	T1 (ms)	F2 (N/kg)	T2 (ms)	F_b (N/kg)	TF_b (ms)
S1	30.68 (±1.05)	17.00 (±2.00)	19.18 (±.93)	68.00 (±2.00)	-18.54 (±0.37)	20.00 (±1.00)
S2	25.02 (±8.31)	20.00 (±0.00)	24.22 (±1.15)	52.00 (±5.00)	-17.76 (±1.30)	30.00 (±3.00)
S3	35.85 (±5.04)	20.00 (±0.00)	21.60 (±0.94)	77.00 (±10.00)	-17.75 (±0.10)	20.00 (±4.00)
S4	27.74 (±3.84)	20.00 (±0.00)	22.08 (±0.58)	69.00 (±11.00)	-19.20 (±0.90)	26.00 (±2.00)
S5	6.61 (±.97)	16.00 (±6.00)	21.05 (±1.48)	79.00 (±26.00)	-8.87 (±0.87)	64.00 (±9.00)

Table 16. Ground Reaction Force (measured as body weight)

	FB			CH			DB			RB		
	F1	**F2**	**F_b**	**F1**	**F2**	**F_b**	**F1**	**F2**	**F_b**	**F1**	**F2**	**F_b**
S1	2.9	2.1	1.6	1.3	1.8	1.0	1.5	2.0	1.2	3.1	1.9	1.9
S2	1.6	3.7	1.5	1.1	2.6	0.6	1.8	2.9	1.5	2.5	2.5	1.8
S3	3.1	2.3	1.7	1.3	2.1	1.4	3.1	2.1	1.8	3.7	2.2	1.8
S4	1.4	2.5	1.2	0.9	2.3	0.7	1.1	2.5	1.0	2.8	2.3	2.0
S5	0.9	2.5	1.2	1.0	1.7	0.6	0.9	2.0	0.8	0.7	2.1	0.9
GP	**2.0**	**2.6**	**1.4**	**1.1**	**2.1**	**0.9**	**1.7**	**2.3**	**1.2**	**2.6**	**2.2**	**1.7**

APPENDIX B - FIGURES

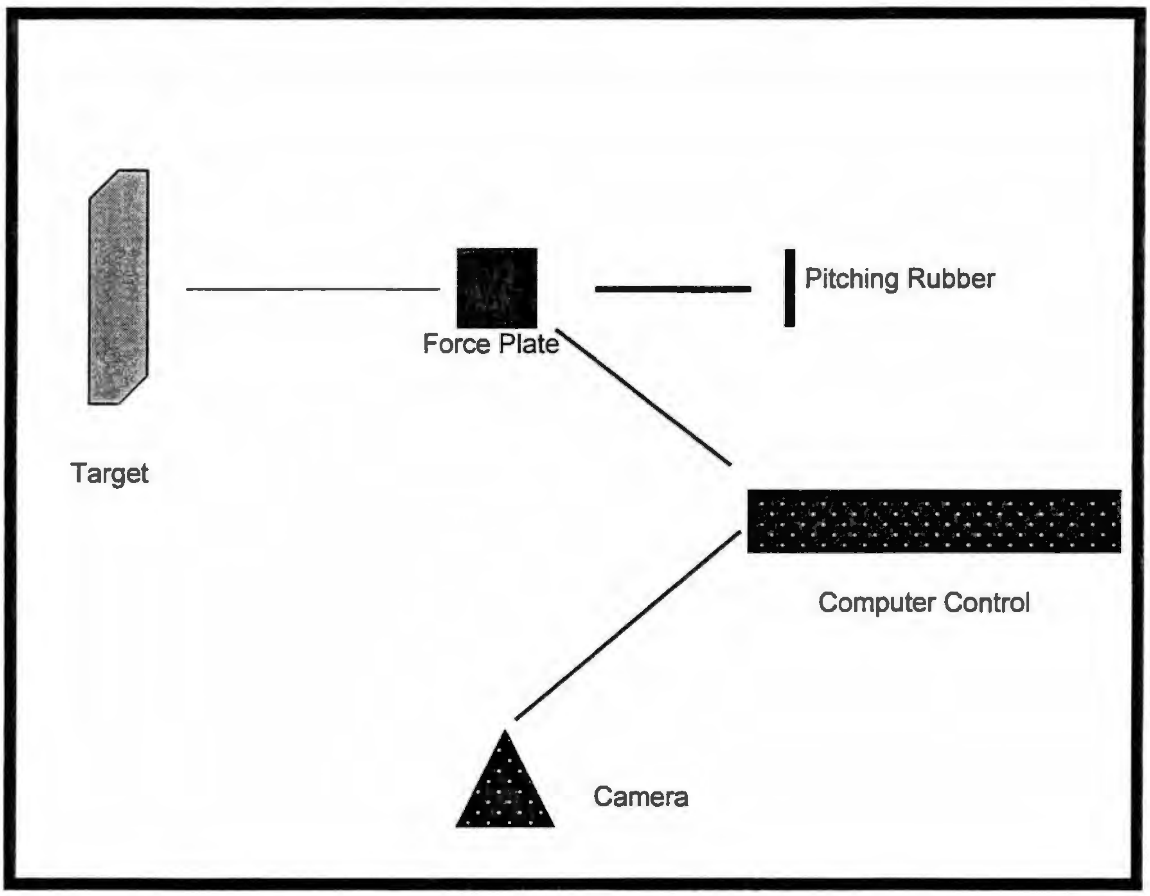

Figure 1. Experimental Setup

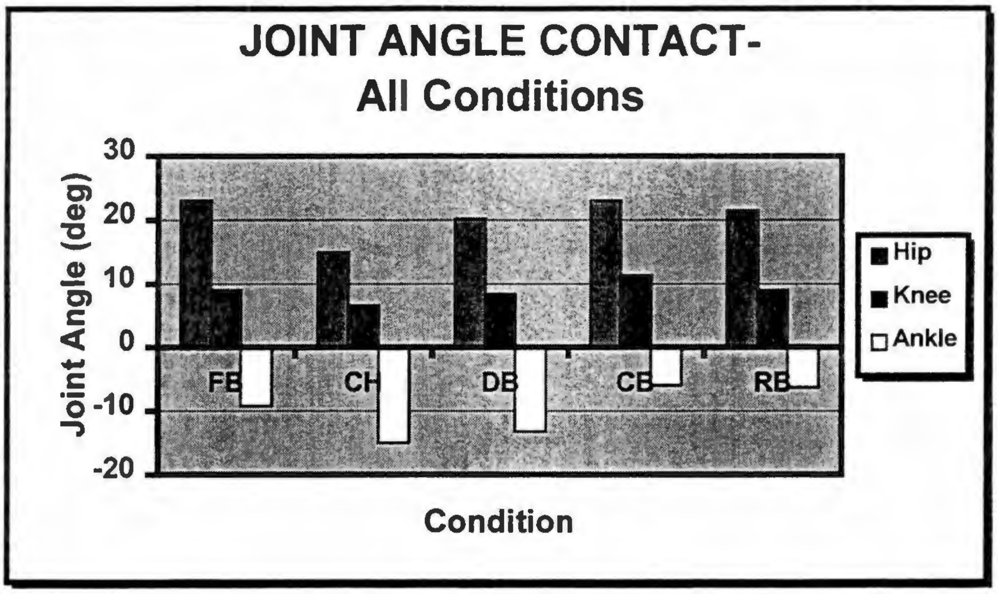

Figure 2. Joint Angle at Contact for Hip, Knee and Ankle

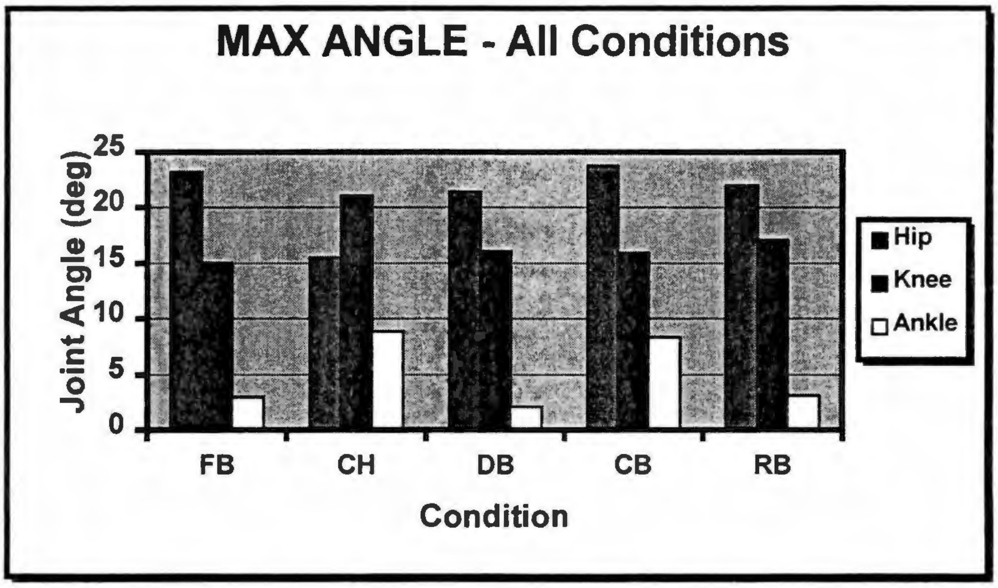

Figure 3. Mean Maximum Joint Angle for Hip, Knee and Ankle

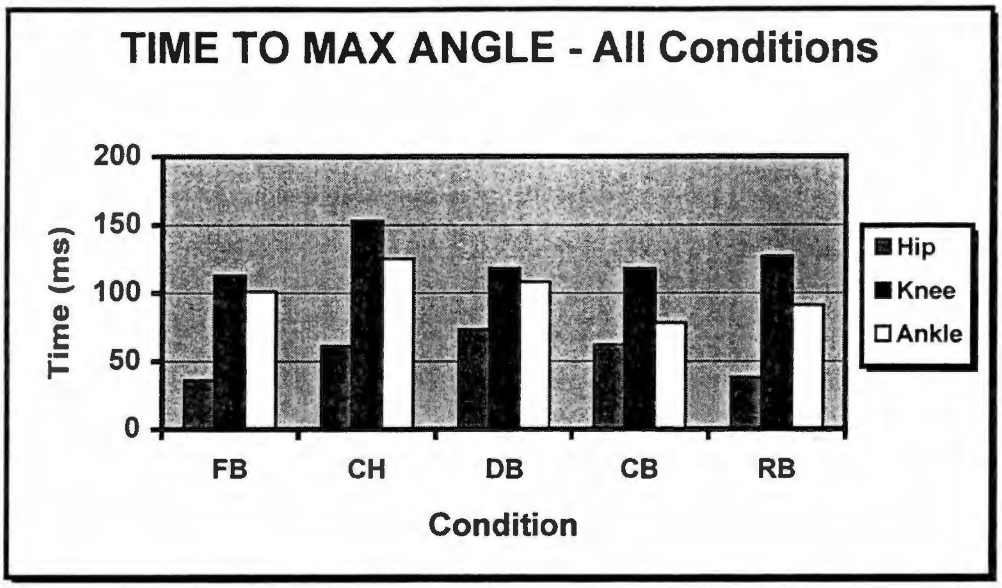

Figure 4. Mean Time to Maximum Angle for Hip, Knee and Ankle

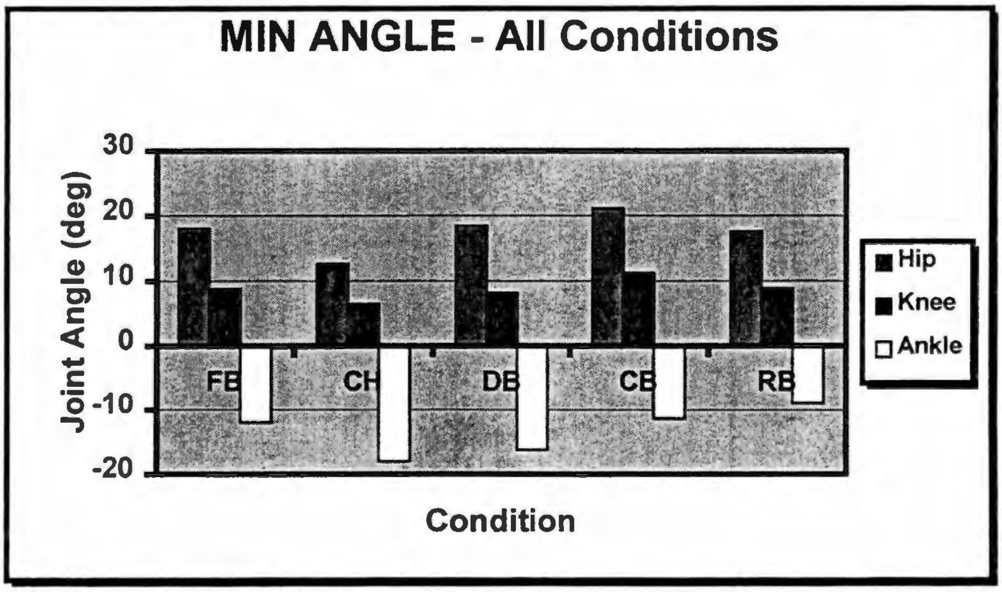

Figure 5. Mean Minimum Joint Angle for Hip, Knee and Ankle

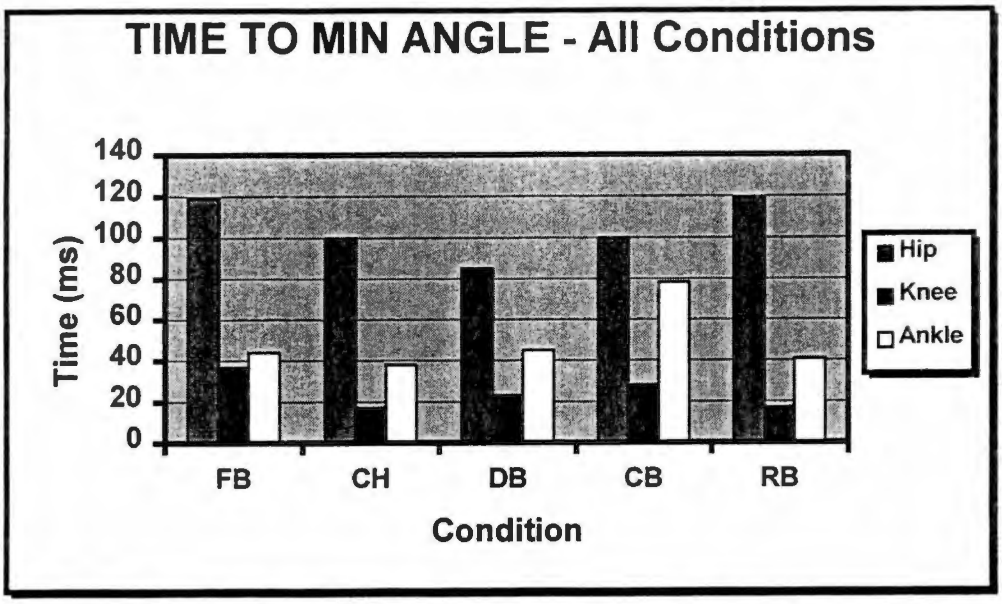

Figure 6. Mean Time to Minimum Angles for Hip, Knee and Ankle

APPENDIX C - INFORMED CONSENT

INFORMED CONSENT STATEMENT

Biomechanics of the Lower Extremity during a Windmill Style Fast-pitch

You are invited to participate in a research study. The purpose of this study is to determine the magnitude of ground reaction forces and kinematic responses created by the stride leg in selected pitches.

INFORMATION

You are invited to attend a single one-hour session of data collection. The test session will involve the measurement of anthropometric and biomechanical data through the use of a measuring tape, meter stick, force platform, and a video camera. You will perform five trials of each type of pitches (fastball, dropball, change-up, riseball and curveball) in a random order. The force platform will be used to measure ground reaction force and moments under the foot during landing of the stride leg while performing each pitch. Data from the force platform and video will be combined and mathematical calculations will be performed to determine the joint moments and muscle forces in the lower extremity.

Anthropometric measurements (height, body weight, and lower extremity girth and length) will be recorded at the beginning of the test session. Retro-reflective markers will be placed on the shoulder, hip, knee, ankle, heel, and head of the fifth metatarsal on the left side of the body for right handed pitchers or the right side of the body for left handed pitchers. One video camera will be used to record each trial to obtain two-dimensional kinematic data.

RISKS

The risks associated with this study are minimal. The types of pitches employed in this study are routinely used in fastpitch softball competition and practice. The total number of pitches to be performed in the testing session are negligible (maximum 25 pitches in addition to the warm-up), as compared to the number of pitches thrown in a typical game or practice, which ranges from 100 to 300 pitches. In addition, you will perform a pitching and stretching warm up routine. Furthermore, the subjects chosen for this study will be active in this activity at the time of data collection.

EMERGENCY MEDICAL TREATMENT

In the event of physical injury resulting from your participation in this research, standard first aid procedure will be administered as necessary. At least one researcher with a basic knowledge of athletic training/first-aid procedures will be present at each testing session. The University of Tennessee does not automatically provide reimbursement for medical care and/or other compensation for any injury resulting from your participation in the data collection.

__________**Participant's initials**

BENEFITS

The purpose of this study is to gain a better understanding of the ground reaction forces and kinematic responses during the landing of the stride leg in windmill pitches. The result of this research may have possible applications for identifying injury mechanisms, injury prevention, and performance enhancement for windmill style fastpitch athletes. Benefits from participating in this study include the opportunity to learn about individual biomechanical characteristics relative to your pitching technique. All parameters of the study will be available for review by each subject upon request.

CONFIDENTIALITY

Information about the subjects will remain confidential during and after the study. Subjects will be coded numerically and referred to by a subject number during analysis and in the written report. Only the primary investigator and faculty advisor will have access to subject information and data. Data will be stored on the hard disk of the computers in the Biomechanics/Sports Medicine Lab during the study, and will be backed up onto floppy disks/zip cartridge and erased from the hard disk after the completion of the study. Subject information sheets, videotapes, back up floppy disks/zip cartridges, and informed consents will be stored in a locked office in the HPER building for the duration of the study and three years thereafter.

CONTACT

If you have questions at any time about the study or the procedures, or you experience adverse affects as a result of participating in this study, you may contact Traci Haydu at (423) 974-5111 or Songning Zhang as (423) 974-1271. If you have questions about your rights as a subject, contact the Compliance Section of the Office of Research at (423) 974-3466.

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from this study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed, your data will be destroyed.

CONSENT

I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Participant's signature ______________________________ Date ____________

Investigator's signature ______________________________ Date ____________

Traci Haydu. BS
HPER Bldg., Rm 135 (974-5111)

Songning Zhang, PhD
HPER Bldg., Rm 337 (974-1271)

APPENDIX D - DATA FORMS

Medical History Form

Name: ______________________ **Date:** ______
Height: ______ **Weight:** ______ **Age:** ______

Physical Activity Level:
___ light (1-2x/week)
___ moderate (3-5x/week)
___ heavy (6-7x/week)

Years pitching experience: In college __________ Total_____________

Check the types of pitches you throw
___Fastball
___Dropball Other: _________________________
___Riseball
___Curveball
___Change-up

Answer **YES** or **NO** to the following questions.

Past History:

Have you ever had:	**Yes**	**No**	**If Yes, When? What?**
Upper extremity surgery/injury	( )	( )	_________________
Lower extremity surgery/injury	( )	( )	_________________
Back pain or injury	( )	( )	_________________

Present symptoms review
Have you recently had:

Upper extremity surgery/injury	( )	( )	_________________
Lower extremity surgery/injury	( )	( )	_________________
Back pain or injury	( )	( )	_________________

SUBJECT INFORMATION

NAME: ______________ SUBJECT #: _____ DATE: _____ AGE: _____

WT (N): ______ HT: _______ YRS EXPERIENCE: ____

ANTHROPOMETRIC DATA

	TRIAL	PROX HT	DIST CIRCUMFERENCE	LENGTH	ANK MOMENT ARM
	1	______	______________	______	______________
FOOT	2	______	______________		
	3	______	______________		
	MEAN	______	______________		

	TRIAL	PROX CIRCUMFERENCE	DIST CIRCUMFERENCE	LENGTH
	1	______________	______________	______
LEG	2	______________	______________	
	3	______________	______________	
	MEAN	______________	______________	

	TRIAL	PROX CIRCUMFERENCE	DIST CIRCUMFERENCE	LENGTH
	1	______________	______________	______
THIGH	2	______________	______________	
	3	______________	______________	
	MEAN	______________	______________	

COND ____		STRIDE LENGTH ______
1.	__________	__________
2.	__________	__________
3.	__________	__________
4.	__________	__________
5.	__________	__________

COND ____		STRIDE LENGTH ____
1.	__________	__________
2.	__________	__________
3.	__________	__________
4.	__________	__________
5.	__________	__________

COND ____		STRIDE LENGTH ______
1.	__________	__________
2.	__________	__________
3.	__________	__________
4.	__________	__________
5.	__________	__________

COND ____		STRIDE LENGTH ______
1.	__________	__________
2.	__________	__________
3.	__________	__________
4.	__________	__________
5.	__________	__________

COND____		STRIDE LENGTH ______
1.	__________	__________
2.	__________	__________
3.	__________	__________
4.	__________	__________
5.	__________	__________

COND1: FASTBALL
COND2: CHANGE-UP
COND3: DROPBALL
COND4: CURVEBALL
COND 5: RISEBALL

VITA

Traci Lee Haydu was born in Toledo, Ohio on March 12, 1971. She attended public schools in Petersburg, Michigan and Toledo, Ohio. She graduated from Whitmer High School in Toledo in 1989. In September 1989, she entered Eastern Michigan University on an athletic scholarship for Varsity Softball. There she received a Bachelor of Science degree in 1994 with an emphasis in Sports Medicine. Upon graduation, she accepted the position as the Assistant Director at the Center for Sports Medicine and Fitness in Ypsilanti, Michigan. In August of 1996, Ms. Haydu entered the graduate school at the University of Tennessee, Knoxville in the Department of Human Performance and Sport Studies to pursue a Master of Science degree in Exercise Science - Kinesiology. In 1997 she accepted a graduate assistantship in the Employee Fitness Program at the University of Tennessee Medical Center. In 1998 she was awarded a graduate teaching assistantship in the Sport and Physical Activity Program.

Following graduation in May, she will remain at the University of Tennessee to pursue a Doctor of Philosophy degree in Education with an emphasis in Exercise Science. Ms. Haydu will continue teaching in the Sport and Physical Activity Program in addition to assisting in the maintenance and management of the Biomechanics/Sports Medicine Lab. She is currently a member of the American College of Sports Medicine.