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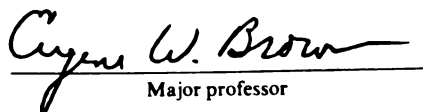
A Three-Dimensional Analysis of the Windmill
Style of Softball Delivery for the
Fast and Change-Up Pitching

presented by

Sang-Yeon Woo

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Physical Education
and Exercise Science


Major professor

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By

Sang Yeon Woo

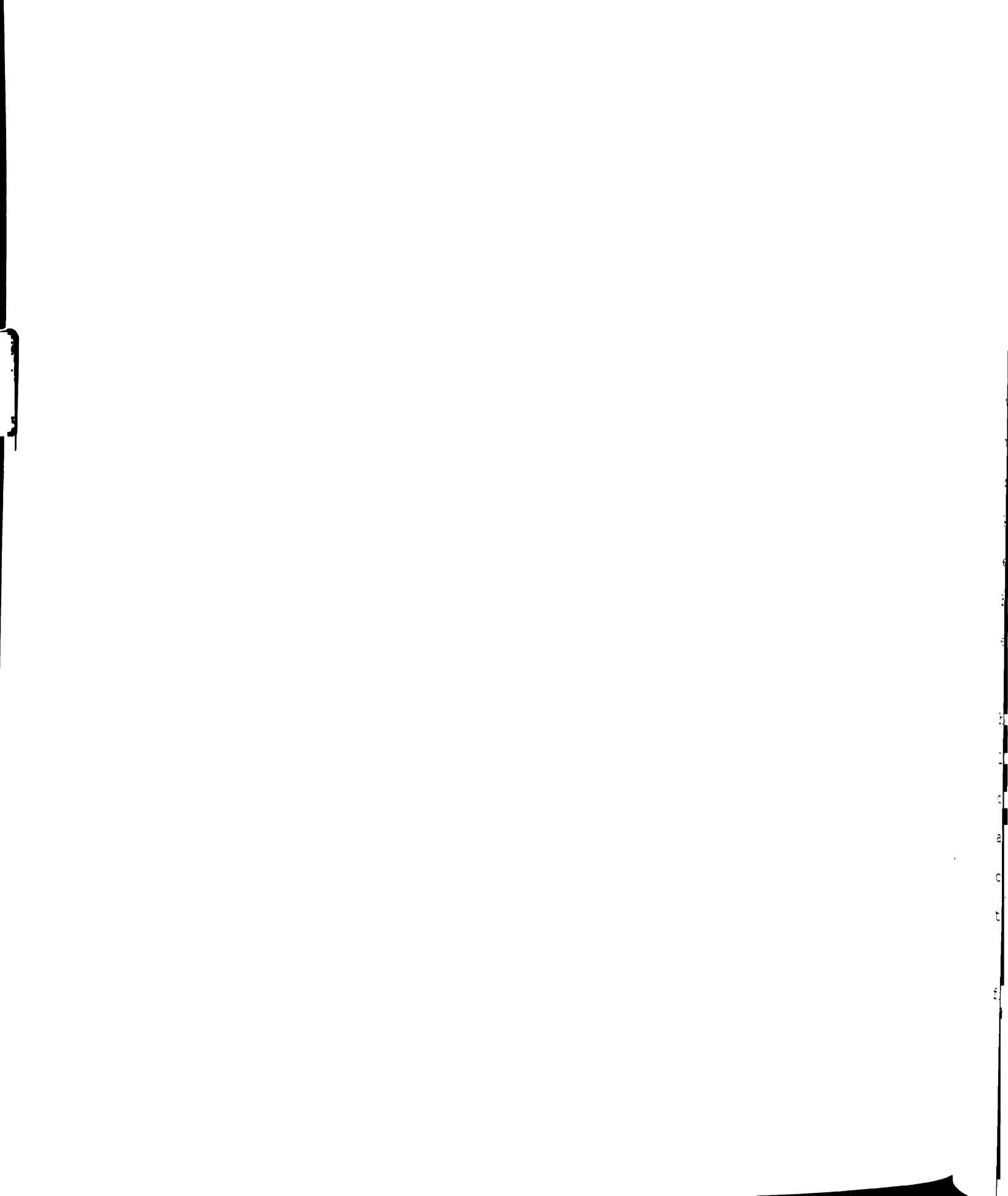
A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
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DOCTOR OF PHILOSOPHY

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ABSTRACT

A THREE-DIMENSIONAL ANALYSIS OF THE WINDMILL STYLE OF SOFTBALL DELIVERY FOR FAST AND CHANGE-UP PITCHING

BY

SANG YEON WOO

The purpose of this study was to investigate the windmill style of softball delivery for the fast and change-up pitches of three female groups from middle school, high school, and college. This investigation examined the kinematic and kinetic characteristics of the upper extremity, the factors that contributed to and differences between the magnitude of ball velocity, and the force exerted against the ground during the pitching motion.

The volunteers for this study were 18 right-handed highly skilled female pitchers who participated in softball leagues. Each subject performed three trials of each style of pitching and the best performance was selected for analysis. They were videotaped using two high speed video cameras with the frame rate being 60 Hz. This data was then reduced to 3D coordinates using the DLT method.

It was concluded that the mean time for the fast pitch from the ground to the point of ball release was less than

for the change-up pitch. The major contribution factors to ball velocity were the flexion of the elbow and shoulder and also the hip. An increased stride length above 90% of the subject's height did not have a major impact on ball velocity. The normalized maximum mean value of the vertical ground reaction force for both style of pitches among the three groups differed little.

Performance differences were visible between the middle school subjects on the one hand and high school and college subjects on the other. The difference in ball velocity between the fast and change-up pitches for middle school subjects were small compared to the other two groups. Relatedly, the resultant joint torque at the shoulder and elbow were greater in high school and college subjects than in middle school subjects. Also, high school and college subjects showed greater peak angular velocity than middle school subjects.

DEDICATION

This dissertation is dedicated to my parents for their
inspiration and guidance.

To my sister, Guisook Woo, for her encouragement and
support.

I love you.

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CHAPTER I

INTRODUCTION

Softball is one of the most popular recreational sports and is increasing in popularity throughout the world. About 40 million people play softball in the world (Pagnoni & Robinson, 1990). According to the official report of the International Softball Federation (ISF) (1994), teams from 86 countries are registered as members of the ISF.

According to Kneer and McCord (1987), softball is the most popular team sport in the United States. Of all amateur sports associations in the United States, the Amateur Softball Association (ASA) is the largest, with 256,769 registered teams and 60,000 umpires. These teams played more than five million games in 1994 (Dickson, 1994; The Official Publication of the International Softball Federation, 1994). Dickson (1994) has estimated that more Americans of all ages and social classes play softball than any other single sport. Outside the ASA, softball play includes an additional 11,000 high school teams, more than

56,000 junior Olympic teams, 85,000 teams of the Slow-pitch Softball Association, and thousands of unregistered and unsanctioned teams (Dickson, 1994). Also, the National Collegiate Athletic Association (1993) lists 607 women's teams (Division I: 178 teams, Division II: 181 teams, and Division III: 248 teams) that participate in collegiate leagues. Softball has also become an important part of physical education and recreation programs in junior and senior high schools in the United States (Paganoni & Robinson, 1990).

A crucial aspect of the game of softball is the performance of the pitcher. More than any other player, the pitcher holds the key to the potential success of the team, particularly in fast pitch softball (Kirby, 1969; Omand, 1974; Jones & Murray, 1978). In fact, several authors (Dobson & Sisly, 1971; Kneer & McCord, 1987; and Kinne, 1985) claim that the pitcher may control 75 to 80 percent of the game's outcome. As a result, most teams have at least three to five pitchers. Several pitchers are needed because (a) prolonged strenuous activity may cause injuries, (b) replacements may be needed when one pitcher is not performing well, and (c) many teams play several games per week during their season and need rested pitchers for each game.

With the current popularity of the sport and the importance of the pitcher to a team's success, clearly a close examination of pitching techniques would be valuable to a large number of individuals interested in softball. Though, research has been conducted on many aspects of softball, there is a paucity of research on the different methods of pitching with regard to velocity and accuracy. One possible reason for the lack of this type of research may be the complexity of analysis associated with the array of pitches employed in softball (e.g., fast ball, rise ball, drop ball, curve ball, change-up ball, and knuckle ball).

Even though players employ many different types of pitches, they commonly use two basic styles of delivery, the windmill and the slingshot, of which the former is more popular. Most of the top-level pitchers use the windmill delivery to throw fast balls. Kirby (1975) has stated that the windmill delivery allows a greater degree of arm swing in comparison to the slingshot throw. The windmill delivery enables the pitcher to develop greater pitch velocity and to better conceal the grip on the ball during the execution of a pitch. Elliot, Grove, Gibson, and Thurston (1986a) also support the windmill style of delivery as having the potential for creating greater ball velocity than the slingshot delivery. According to Schroeder and

Hinderliter (1981), the windmill is the most popular style and provides the most ball momentum. In addition, the windmill style may be more popular because it requires fewer adjustments with respect to the coordination of body parts. Also, the windmill is generally less fatiguing in comparison to the slingshot delivery (Hofstetter, 1980b; Regitano, 1982).

For a right-handed pitcher (see Figure 1.1), the windmill style of pitching features a complete revolution of the right arm in a clockwise, underhand motion. The delivery is initiated by swinging both arms forward and upward, reaching out without straining. At the same time, the pitcher's weight shifts, from support on both feet, to support primarily on the right foot (see Figure 1.1a-1.1c). From this position the right hand pulls the ball out of the glove as the pitching arm continues swinging upward. At this point, the left foot lifts off the rubber and starts moving forward (see Figure 1.1c-1.1d). The arm continues up and back, with the pitcher's weight still on the right foot, the left foot continues moving toward home plate. The pitching arm straightens out and the wrist cocks back as the downward swing begins to gather momentum (see Figure 1.1e-1.1h).

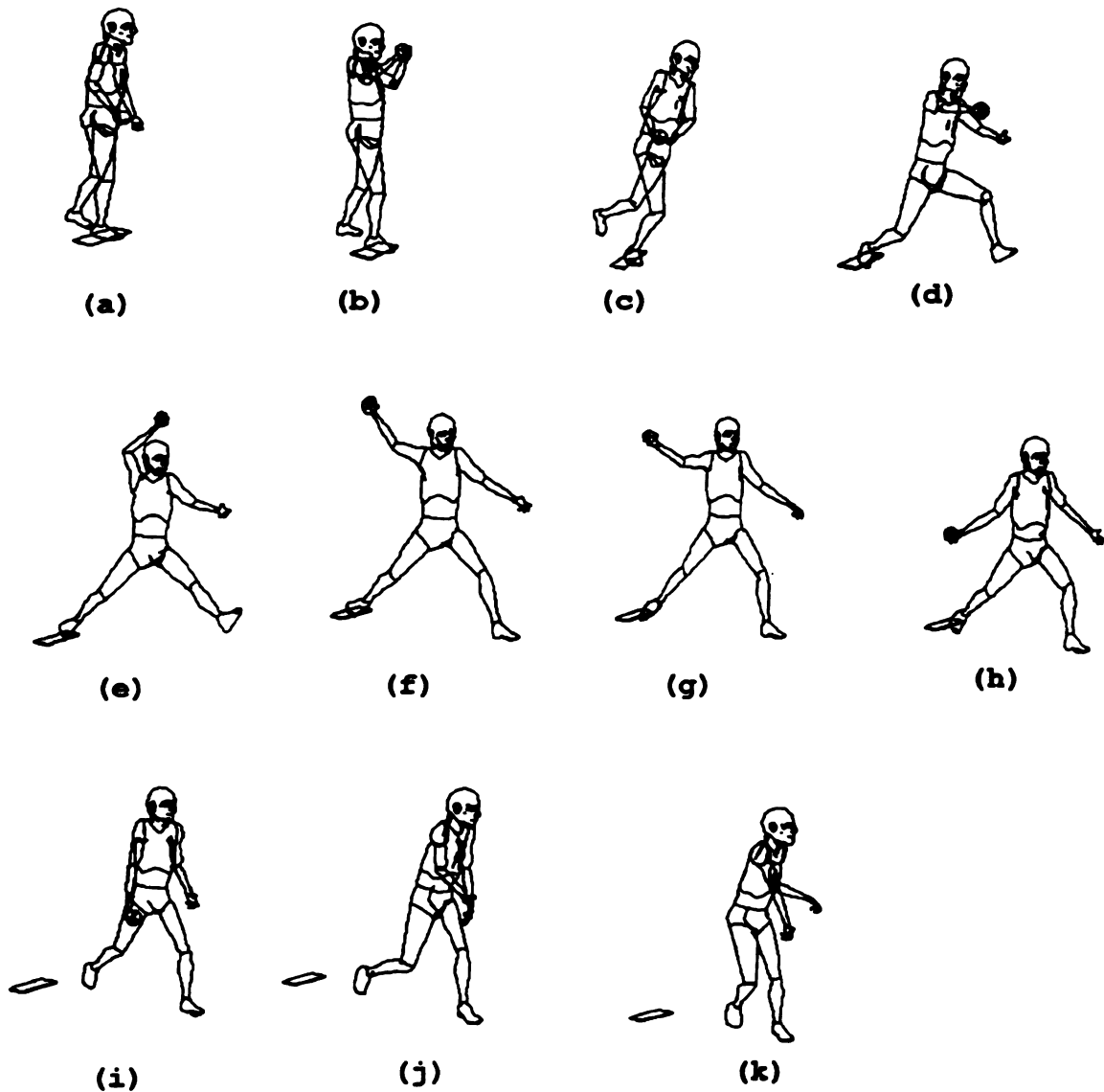


Figure 1.1 The windmill softball pitching motion: (a) stride foot takeoff from force platform, (e) highest point of the pitching arm, (f) stride foot contact with wooden frame, and (i) ball release

At this point, the pitcher continues to push back against the rubber with the right foot. Then the left foot completes its glide toward the home plate and the body weight is shifted onto the left foot as the pitcher regains balance of the body. The whipping motion of the arm continues. However, now, the power of the legs and body are used to thrust the weight of the body forward against the braced left leg. Just before the release position is reached, the upper part of the body, still cocked back for the final powerful snap, whips the ball out of the hand, while the body is turned directly toward the plate (see Figure 1.1h-1.1i). The pitching motion continues on to the follow-through (see Figure 1.1j-1.1k) (Kirby, 1975; Feigner, 1980; Drysdale & Harris, 1982; Regitano, 1982; Werner, 1994a).

Because of the importance of pitching in this popular sport, it is logical to assume that much research would have been conducted on the variables of the windmill pitch. However, this is not the case. As a result, much remains to be learned about the mechanics of the softball windmill pitch.

Wells and Luttgens (1982) have stated that ballistic sports activities, such as the windmill pitch, are characterized by high-velocity limb movements that are initiated by vigorous muscular contraction and completed by

a continuation of the momentum generated by these muscular contractions. Softball pitching, similar to other repetitive high velocity arm activities, such as the baseball pitch, tennis serve, and volleyball spike, exposes the shoulder girdle, shoulder joint, elbow, wrist, and hand to relatively large forces and torques. As a result, the repetitive, high velocity nature of throwing can lead to serious upper extremity problems. Recently, several reports have described softball-related injuries and their prevention (Loosli, Reque, Garrick, & Hanley, 1992; Tanabe, Nakahira, Bando, Yamaguchi, Miyamoto, & Yamamoto, 1991; Wheeler, 1984). During the 1989 women's NCAA softball tournament championship, Loosli et al. (1992) conducted an injury survey of the pitchers on eight college teams ranked among the top 15 competitive teams in the U.S.A. The injuries and complaints concentrated primarily on the region of the shoulder, elbow, and forearm. Tanabe et al. (1991) have stated that fatigue fractures of the ulna have been caused by repeated use of the forearm in sports such as softball, tennis, and volleyball. The incidence of reported fractures in softball pitchers has been greatest in the middle part of the ulna. These observations imply that fatigue fractures of the ulna in

pitchers of fast-pitch softball must be torsionally induced.

An awareness that injury problems exist in repetitive high velocity shoulder movements has spurred individuals, who are involved with fast-pitch softball, to investigate injury prevention strategies that might allow players to pitch more safely and to avoid some of these injuries (Loosli et al., 1992). Young pitchers and their parents also need to be made aware of the potential for injuries related to pitching and the risks involved in being a softball pitcher. Though softball is a popular sport in middle and high school, researchers have focused primarily on college and semi-professional players.

By understanding the factors that affect the motions of the pitching arm, it would be possible to (a) gain an increased understanding of the mechanisms that produce the speed of the softball, (b) help coaches advise their athletes on appropriate pitching styles, and (c) prevent related injuries.

The purpose of this research is to investigate kinematic and kinetic parameters of the windmill softball pitching motion among three groups of highly skilled female pitchers (middle school, high school, and college). In order to determine the relative contribution of each of the body

segments to a skill, it is necessary to use a segmental analysis approach, whereby the kinematic and kinetic characteristics of the segments are determined (Plagenhoef, 1971).

According to Elliott et al. (1986b), sagittal plane motion of the three major joints of the upper limb (shoulder, elbow, and wrist) accounted for 90% and 96% of the release velocity of the fast and curve balls, respectively. However, most available literature on softball pitching has focused on the windmill pitching motion and has mostly investigated kinematic aspects (Alexander & Haddow, 1982; Bridges, 1982; Guenzler, 1979; Kinne, 1985 and 1987; Verwey, 1959; Wolter, 1965; Zollinger, 1973). Also, most of the studies reported to date have been limited to the analysis of two-dimensional (2D) kinematics. Only two studies, Alexander (1978) and Parrish (1981), used a three dimensional (3D) analysis. Parrish examined 3D resultant linear velocities of the ball, the right elbow joint center, and the right shoulder joint center; the orthogonal components of velocities of the ball; the 3D angular displacement and velocity of the right elbow joint; and, the body position at release.

Parrish's study reported 3D quantitative kinematic data of the throwing arm for the overarm and sidearm softball

throw, but no data on kinetic parameters. Also, no studies have dealt specifically with kinetic data at the shoulder, elbow, and wrist joints of the throwing arm. Alexander (1978) studied the relative velocities of the three segments of the upper extremity in the softball pitching motion. She investigated linear and angular velocity and acceleration of the shoulder, elbow, wrist, and fingertips. She also collected kinetic data (ground reaction force and the resultant torques at the shoulder, elbow, and wrist in the primary plane of motion). She, however, collected only 3D data of the forearm, while the other body segments were analyzed by 2D.

Unlike softball, much has been written in the movement analysis literature about the patterns of the limb that occur in other ballistic "throwing" skills (Feltner & Dapena, 1986; Chung, 1988). For example, 3D kinematics and kinetics studies of the throwing arm have been reported for baseball and volleyball. Feltner and Dapena (1986) obtained 3D quantitative information on the torques at the shoulder and elbow joint of the throwing arm in full-effort baseball pitching. Feltner (1987) studied 3D segment interactions of the throwing arm for overarm fastball pitching in baseball in order to clarify the mechanical cause-effect relationships that produce the baseball

pitching motions. He collected kinematic data of the elbow flexion/extension angle, angular velocity of the throwing arm, inertial angular acceleration, and linear acceleration of the shoulder. He also analyzed kinetic data (joint torque, and the motion-dependent forces and torques at the shoulder and elbow joints).

Sakurai, Ikegami, Okamoto, Yabe, and Toyoshima (1993) examined upper extremity movement in fastball and curveball pitching in baseball. They compared joint angle kinematics of the throwing limb in the period from the preperation phase up to the release of the ball. To accomplish this, they used 3D cinematography as a method for determining the shoulder, elbow, radioulnar, and wrist joint angles.

Chung (1988) investigated arm swing phase of the volleyball spike. He studied the patterns of motion of the striking arm and the muscular activities responsible for this movement. He collected the following kinematic data: location, velocity, and acceleration of the center of mass of each segment; location and velocity of the center of mass of the whole body; joint angles and angular velocities; and ball velocity. He also studied the angular momentum, force, and torque of the swinging arm.

Unlike the previously mentioned sports, in softball, 3D analysis of the pitching motion has not been adequately

conducted. Hence, there is a deficiency of more accurate and precise data on the mechanics of the pitching motion, especially regarding the examination of the upper extremity and ground reaction force. The current study was designed to analyze the patterns of the fast and change-up ball pitching motion, and to compare the similarities and differences among three groups of subjects (middle school, high school, and college). The primary kinematic parameters investigated were stride length, ball velocity, and angular displacement and velocity of the pitching arm. The contributions to ball velocity by the angular velocity at the shoulder and elbow joints were also investigated. The main kinetic parameters investigated were the forces and torques at the shoulder and elbow joints of the pitching arm and the ground reaction force of the pivot foot during the pitching movements. These joint torques were an indication of the most important muscle groups acting at a particular instant in the performance of a skill.

Statement of the Problem

The purpose of this study was to investigate the softball windmill pitching motion of the throwing arm among three highly skilled female groups (middle school, high school, and college). The three main questions that this investigation sought to answer were: (1) What are the

kinematic and kinetic characteristics of the upper extremity in the fast and change-up pitching styles of windmill softball pitching ? (2) What kinematic and kinetic factors contribute to and differentiate between the magnitude of the ball velocities ? and (3) What forces are being exerted against the ground during the performance of each pitch ? The following factors were examined: (1) ball velocity; (2) stride length; (3) angular displacement and velocity of each segment; (4) force and torque at the shoulder and elbow joints; and (5) ground reaction force. Potentially, an understanding of correct pitching mechanics in throwing the fast and change-up pitches could provide information to coaches to assist their pitchers in developing command and control of ball velocity, accuracy, and technique, and to possibly prevent injuries.

Limitations

Several limitations may have had an effect on the results of this study.

1. The filming took place in a special, non-competitive situation and, as a result, the subjects may not have performed exactly as they would have in league play.
2. The calculation of the body landmark coordinates from videographic data has inherent errors due to difficulties in the identification and digitization of anatomical landmarks.

These errors subsequently may have affected the accuracy of computed kinematic and kinetic parameters.

3. Since the actual inertial segment parameters of the subjects could not be accurately measured, the study relied on anthropometric data investigated before and this may have affected the computations.

4. Limitations to accuracy were imposed by the image resolution and field rate of the video cameras used to record to the movements of the subjects.

Definitions of Terms

Abduction at the shoulder joint. The upward motion of the arm away from the side of the body in the frontal plane, from 0° to 180° (see Figure 1.2a).

Adduction at the shoulder joint. The downward motion of the arm toward or beyond the mid-line of the body in the frontal plane (see Figure 1.2a).

Change-up pitch. A type of pitch purposely thrown with significantly less speed than a fast pitch.

Extension at the elbow joint. A movement of the forearm relative to the arm that causes an increase in the angle between them (see Figure 1.3).

Extension at the shoulder joint. The downward motion of the arm in the sagittal plane (see Figure 1.2b).

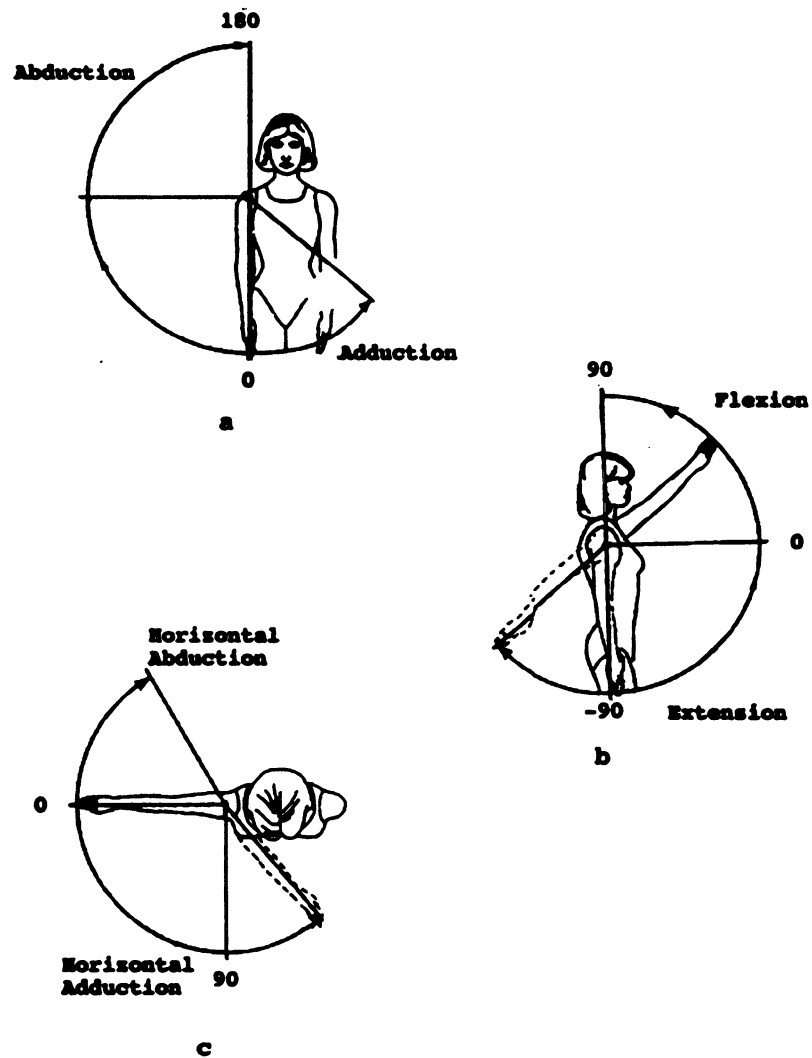


Figure 1.2 Movements of the arm at the shoulder joint: (a) abduction-adduction, (b) flexion-extension, and (c) horizontal abduction-adduction.

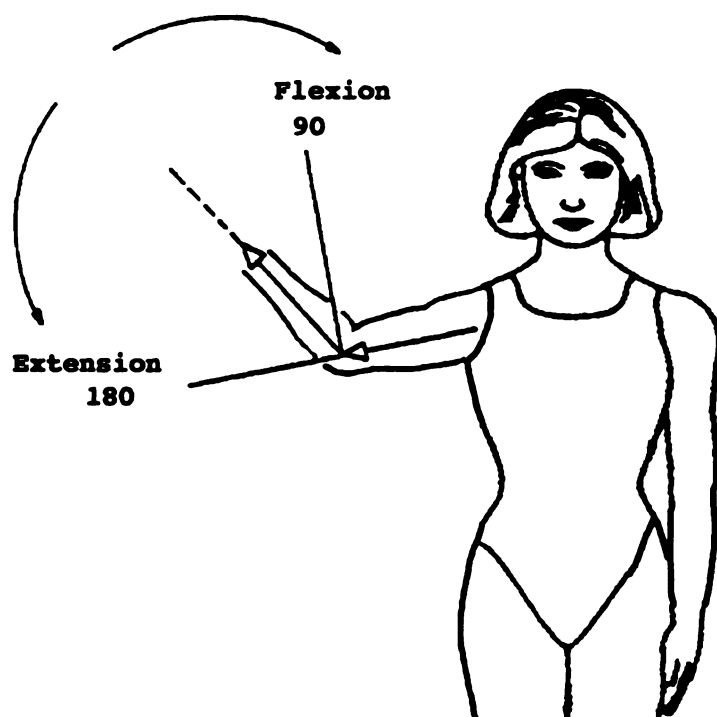


Figure 1.3 Movements of the elbow.

Fast pitch. A pitch that is intended to travel as fast as possible across home plate.

Flexion at the elbow joint. A movement of the forearm relative to the arm that causes a decreases in the angle between them (see Figure 1.3).

Flexion at the shoulder joint. An upward motion of the arm in the sagittal plane (see Figure 1.2b).

Horizontal abduction at the shoulder joint. A posterior movement of the arm in the transverse plane (see Figure 1.2c).

Horizontal adduction at the shoulder joint. An anterior and medial movement of the arm in the transverse plane (see Figure 1.2c).

The global reference frame. The inertial reference frame fixed to the environment.

The local reference frame. The non-inertial reference frame whose origin is at the center of mass of the subject in motion and rotates with the subject's body.

Joint force. The sum of all the forces exerted by a segment on an adjacent segment through the muscles, ligaments, bone, skin, nerves, blood vessels, etc. that connect the segments at their common joint.

Joint torque. The sum of all the torques exerted about the joint center by a segment on an adjacent segment through the

forces exerted by the muscles, ligaments, bone, skin, nerves, blood vessels, etc. that connect the segments at their common joint.

CHAPTER II

REVIEW OF RELATED LITERATURE

This chapter presents a review of the literature related to movement patterns used in the windmill style of pitching in softball, as well as methodological approaches and quantitative analyses employed in the study of the shoulder and elbow joints of the throwing arm. In dealing with methodological approaches, the studies conducted so far are described in this chapter. The findings of these studies are examined in the quantitative analysis section.

Movement Patterns Used in the Windmill Style of Softball Pitching

The windmill pitching style is often divided into three major movement phases: presentation, execution, and recovery. In the preparation phase (see Figure 1.1a-1.1d), the body moves from a static starting position into a position which allows for proper performance of the pitch (Lopiano, 1978; & Kreighbaum & Barthels, 1981). The execution phase (see Figure 1.1e-1.1i) is that portion of the delivery in which the body moves in such a way as to accomplish the purpose of the task (Kreighbaum & Barthels, 1981). Finally, the recovery phase (see Figure 1.1j-1.1k),

also known as the follow-through, occurs after the ball is released and is characterized by a return of the body to a quasi-static state (Kreighbaum & Bathels, 1981).

Preparation

To begin the delivery, the pitcher's feet are placed approximately shoulder width apart with the heel of the trail foot in contact with the front half of the pitcher's rubber and the toes of the lead foot in contact with the back edge of the rubber (Drysdale & Harris, 1982; Feigner, 1980; Hay, 1978; Kirby, 1975). This positioning of the feet provides an advantage to gain a larger stride length in order to generate forward momentum. Feigner (1980) stated that the front foot should be turned slightly toward the throwing arm side and the back foot pointed slightly in the opposite direction in order to facilitate proper hip and shoulder rotation later in the pitching motion.

Execution

Hofstetter (1980b) provided a comprehensive analysis of the windmill delivery. She indicated that two of the most important elements of the windmill pitch are the stride length and the angular velocity of the throwing arm. Most researchers have agreed about the optimum stride length, that is, a longer stride is much more effective. The stride should be extended up to 80% of the standing height

to increase the overall speed of the pitch (Jones & Murray, 1978; Shrader & Everden, 1977).

The execution of the delivery is one of the more complicated actions. As the pitcher shifts the weight to the right foot and steps forward with the left foot, the pitcher's arm begins the windmill motion. During the downswing of the arm (the final 180 degree arc), the pitcher produces most of the forward force. The velocity of the body, generated by the push off of the right foot and the stride of the left foot, is added to the velocity developed by the arm. The pitcher plants the left foot on the ground just before the release, allowing the upper body to rotate sharply counter-clockwise. Werner (1994c) and Sobel (1980) stated that the elbow flexion of the pitching arm throughout shoulder circumduction would cause a transfer of speed to the ball. Jones and Murray (1978) said the backswing must be executed with the elbow flexed in order to allow a whipping motion as the forward momentum of the pitch builds to a peak at the instant of release. At the same time, an increase in the velocity of hip rotation will also result in an increase in the velocity of the ball. Alexander and Haddow (1982) documented the arm motion in the windmill pitch and contended that there must be a definite proximal-to-distal sequence of segment motion in the upper extremity

beginning with the shoulder and progressing to the elbow, wrist, and then fingers. Deceleration occurs in the proximal segments prior to the release of the ball. They reported a definite sequence of segment motions which characterizes the highly skilled performer in the windmill pitch. They indicated that the larger, more proximal segment reaches maximum angular velocity at the earliest point in the motion, followed by the next segment, and finally the most distal segment.

Wolter (1965) presented evidence that the joint of elbow is not fully extended at release. The measurements of the angle of the position of the elbow at release ranged from 158 to 178 degrees of flexion for the slow ball and from 150 to 174 degrees of flexion for the fast ball and from 157 to 178 degrees of flexion for the curve ball. Similarly, Werner (1994c) reported that the average angle of the elbow at release for eight elite pitchers was 139 to 164 in the windmill fast pitch.

Recovery

Recovery is the action that occurs after release. The main purpose of the recovery is to maintain the pitcher's balance (Werner, 1994a). Hofstetter (1980b) stated that the motion of the hips and body, toe drag, and arm should be directed forward. Noel (1978) stated that the pitching arm

should move across the pitcher's body as well as upward. Zollinger (1973) stated that the weight shift of a right handed pitcher should be to the extreme right in order to regain balance and that the pitching hand reach a position that is shoulder high. Alexander (1979) described this action as the hand ending in a position above the head and added that the elbow flexes throughout the recovery.

Methodological Approaches

Segmental Analysis

Most of the mathematical and segmental analysis techniques of the human body were derived from the United States Space Research Program (Dempster, 1955). One of the most often quoted studies from this program is that of Hanavan (1964), which has been used extensively by subsequent researchers in sports biomechanics (Miller, 1970; Plagenhoef, 1971). Hanavan (1964) developed a 15-segment geometric model of the human body. He defined the head as an ellipsoid of revolution and the trunk segments as two elliptical cylinders representing the upper and lower trunk, respectively. He defined all limb segments other than the hands (sphere) as frustums of right circular cones. Whitsett (1963) introduced a geometric human body model consisting of 14 simple geometric solids such as ellipsoid of revolution (head), elliptical cylinder (trunk), sphere

(hands), parallelepiped (feet), and frustum of right circular cones (other limb segments) in a study of dynamic response characteristics of weightless man such as thrust misalignment, maneuvering, and free-body dynamics.

One of the earliest physical education researchers to advocate the use of segmental analysis in examining sports skills was Plagenhoef (1966). He expanded his techniques of segmental analysis to include joint force associated with the acceleration of segmental endpoints (1973).

Dillman (1971) used the technique of segmental analysis to study the relative motions of the three segments of the lower extremity (thigh, shank, and foot) in the recovery phase of sprint running. He simplified segmental models by replacing the muscle force acting to rotate a segment at a joint with an equivalent joint force and couple acting at the joint. Using this model for segmental analysis, he was able to estimate the direction and magnitude of the torques acting at the three joints of the lower extremity.

Miller (1970) utilized the principles of segmental analysis in formulating her model of the airborne phase of springboard diving. She used a four-segmental model based on Havana's model of a movable man (Havana, 1964), for which she developed a series of equations to describe the motion of her model.

Susanka (1974) developed computer programs for segmental analysis techniques to evaluate sports movements. His programs were similar to those previously developed by Plagenhoef; both programs accepted body segment endpoints from film as input to generate displacements, velocity, and accelerations as a function of time. In addition, horizontal, vertical, and resultant joint forces and joint moments were computed. The subject was modeled as a system of fourteen rigid segments (head, trunk, arms, forearms, hands, thighs, shanks, and feet) free to rotate relative to each other at the joints.

Cinematographic and Videographic Studies

Some researchers have done cinematographic studies of the skills of softball pitchers (Wolter, 1965; James, 1971; Zollinger, 1973; Hinson, 1974-1976; Guenzler, 1979; Bridges, 1982; Seevers, 1986; Werner, 1994b). Though their emphases varied, only a few specifically studied the biomechanical techniques of the throwing motion. However, they did provide information for studying general techniques; mechanical variables leading to release; and ball velocity, rotation, and trajectory. Subsequent information in this section provides a general description of cinematographic studies, which includes the purpose of the project, camera usage, and quantifications derived from the analysis. The

findings of these studies are examined in the quantitative analysis section presented later in this chapter.

Wolter (1965) made a cinematographic and goniogramic study of joint actions that occurred during presentation, delivery, and release of fast, slow, and curve ball pitches by four skilled women. She took side-view photographs to compare the body positions of her subjects at ball release. She also measured ball velocity and position of the elbow and radialulnar joints at release.

James (1971) used two high speed cameras to analyze the trajectory of the rise ball and the factors affecting its trajectory. Three highly skilled male pitchers were filmed to obtain a total of 45 pitching sequences. Two high speed cameras operating at 128 f/s were used to capture these movement patterns. Quantification included ball velocity, rates of ball rotation, and the amount of vertical deviation each pitch underwent from a normal parabolic trajectory.

Zollinger (1973) filmed one female subject with two cameras operating at 64 and 65 frame/sec., respectively. Her description included the presentation, wind-up, release, and follow-through. In addition to measurements concerning stride length and the horizontal velocity of the pitch, she computed the torque of the arm about the shoulder joint, and

the torque of the hand-ball system about the wrist joint at release.

Hinson (1974-1976) filmed four female subjects competing in a fast pitch tournament. She analyzed temporal characteristics of the pitches to determine the sequence of motion and the timing involved. The motion for which time was measured included the start to the top of the delivery, start to stride foot contact, foreswing, and complete pitch. Computed values also included ball velocity and stride length.

Knox (1977) examined 20 female starting pitchers participating in intercollegiate team sports to study whether they could produce greater ball velocity by releasing the ball before or after the stride foot hit the ground. She used one high speed camera with 138 f/s to measure the ball velocity.

Guenzler (1979) made descriptive and temporal analyses of the biomechanical techniques and principles involved in throwing the rise ball, drop ball, and change of pace types of softball pitches. Using two cameras (side view-200 frames/sec.; rear view-70 frames/sec.), he filmed five skilled male pitchers who participated in the Tucson AAA softball league. He investigated the grip, stride length, arm action, ball path prior to release, ball release

position, velocity and flight of the ball, and temporal characteristics of pitching.

Bridges (1982) studied mechanical similarities and differences among the fast ball, rise ball, drop ball, curve ball, and change-up pitches of the windmill delivery thrown by an amateur female pitcher of "outstandingly" high ability. Bridges investigated horizontal and vertical release point, stride length, time of follow-through, and ball velocity.

Alexander and Haddow (1982) studied the relative motions of the upper limb segments in the execution of the softball windmill pitch. They filmed four skilled pitchers (two male and two female) using two high speed cameras operated at 100 f/s. They collected data for ball velocity, stride length, and time of ball release.

Kinne (1985) studied specific kinematic and kinetic variables associated with a fast ball, drop ball, and rise ball delivered via the windmill style of pitching. Eighteen female pitchers in a Women's National Fast-Pitch Softball Tournament participated in this study. She collected data on ball velocity, the maximum amount of hip and shoulder rotation during the execution of a pitch, stride length, and the amount of torque about shoulder joint at release.

Seevers (1986) studied how the difference in the finish of a softball cover influenced the velocity and rotation of the ball when it was thrown by six highly skilled male windmill pitchers. She measured ball velocity, speed of rotation of the pitch, stride length, and angular velocity of the pitching arm.

Werner (1994) studied the kinematic variables associated with the fast pitch delivered by the windmill style of pitching. Eight top U.S. female pitchers, who participated in 1994 Softball Peak Camp in Long Beach, California and in the 1991 Pan Am Trials, were videotaped by using the high speed video camera (60 Hz). She measured the stride length, ball velocity, and angular velocity of elbow and shoulder.

Most of the above mentioned and other published research on softball pitching are mostly descriptive in nature and limited to 2D analysis. Only Alexander's study (1978) utilized 3D analysis of softball pitching motion. Using two high speed cameras and a force platform, she determined the relative velocities of the three segments of the upper extremity employed in the windmill style of pitching in softball by four highly skilled softball pitchers (two females and two males). She determined many performance parameters: stride length, ball velocity, ground reaction

force, linear and angular kinematics, resultant forces and moments of the pitching arm.

No studies reported in the literature have specifically dealt with a 3D analysis of kinematic and kinetic characteristics of the shoulder and elbow joints of softball pitching. Since most human motion is curvilinear, the use of 3D cinematographic or videographic analyses is likely to provide more realistic information concerning out-of-plane motion than have 2D planar techniques. Biomechanists have reported on the use of 3D film and video techniques for the analysis of sports skills. Among these, Walton's (1981) technique is most popular in sport research. He developed a generalized approach that required no information regarding the position and orientation of multiple cameras. His technique is based on the "direct linear transformation" (DLT) method, originally introduced by Abdel-Aziz and Karara (1971), that required precisely located control points within the coordinate system.

Feltner (1987) and Feltner and Dapena (1986) used 3D techniques to investigate the resultant joint torques and forces at the shoulder and elbow joints of the throwing arm in baseball. They revealed that torques of small magnitude were present at the shoulder joint until near the moment of stride foot contact and simultaneous horizontal adduction at

the shoulder joint until the instant of ball release. Shortly after the arm reached a position of external rotation, an abduction torque and an internal rotation torque occurred at the shoulder joint. The abduction and internal rotation torques reached their maximum values (70Nm and 90Nm, respectively) just prior to the instant of maximum external rotation. However, both were significantly reduced by the time of the instant of ball release.

Feltner and Dapena (1986) also reported relatively small values for the flexion/extension torque at the elbow joint until approximately halfway between stride foot contact and maximum external rotation, when the elbow began to experience an extension torque. This extension torque (peak value, 20Nm) was present until the instant of maximum external rotation. After that, the flexion/extension torque decreased and was negligible at the instant of ball release.

Horn (1984) calculated the joint forces and torques at the shoulder and elbow joints of the throwing arm of a single major league baseball pitcher throwing a fastball pitch. The procedures used by Horn for coordinate data optimization, smoothing and differentiation also led to several complications. His method produced large

fluctuations in the computed joint force and torque data, which raised doubts about the accuracy of the data.

Elliot et al. (1986b) conducted 3D cinematographic analysis of the fastball and curveball pitches in baseball. Their purposes were to identify both the similarities and differences in pitching techniques and to determine pitching mechanics in throwing the fastball and curveball. They studied six skilled male pitchers. They used the DLT method to obtain 3D coordinate data and computed ball velocity, stride length, 3D elbow angle, height of lead knee above the hip, and angle of thigh, leg, and break.

Force Platform

The use of force platform data is relatively recent in the biomechanics of sports investigations. Ramey (1973) stated:

The force plate has become a useful tool for the study of many types of human motion - the force plate yields some fundamental data and substantially assists in the understanding of the motion involved. In the particular case of the athletic studies, the force plate has been used to identify faults in technique and led to new ways to perform the event. (p. 67)

Alexander (1978) was the only researcher to use a force platform to obtain the ground reaction forces in softball pitching. She revealed that the peak vertical ground reaction forces occur just prior to the release of the ball, while the horizontal peak force occurs much earlier.

Although vertical ground reaction has a very noticeable peak, Alexander (1978) stated that a greater peak for ground reaction forces does not necessitate a better performance. They studied the force plate tracings of a highly skilled football punter, and found that the vertical peak force was significantly and inversely related to the predicted kick distance. However, these authors attempted no real explanation for this phenomenon, and, in fact, few explanations verify this conclusion. It seems more likely that a greater vertical force component could produce a greater force against the ball. A more important quantity in pitching velocity may be the impulse associated with ground reaction forces.

Electromyography

The study of electromyography (EMG) has not been reported in softball pitching. However, the use of this technique could provide insight into the sequencing of muscular involvement in various windmill pitches. The majority of the EMG research on the muscular activity in the throwing arm during the baseball pitch has been conducted by Jobe's research team (Jobe, Moynes, Tibone, & Perry, 1984; Jobe, Tibone, Perry, & Moynes, 1983; DiGiovine, Jobe, Pink, & Perry, 1992). Three studies by Jobe's team combined dynamic thin-wire EMG and 3D cinematography. The

researchers tried to relate the EMG data to the motions of the pitcher. They revealed that the EMG activity of the pectoralis major and latissimus dorsi, from five professional baseball pitchers, began between the instants of stride foot contact and maximum external rotation of the arm, and then continued throughout the remainder of the pitch. Both muscles exhibited slightly decreased EMG activity after the instant of ball release. Triceps EMG activity occurred as the elbow joint reached its maximum flexion angle and the arm reached its position of maximum external rotation simultaneously, and that the triceps EMG activity continued during the period of rapid elbow extension, prior to ball release. During the period of rapid elbow extension and through the instant of ball release, the biceps and brachialis EMG activity was quite small. However, both these muscles demonstrated a rapid increase in EMG activity immediately after the instant of ball release.

Studies Related to Kinematic and Kinetic Parameters

Several authors have focused their research on the measurement of rotation of body segments around their longitudinal axes. This is an important problem in the quantification of human movement, and one that has no consistent solution. Also, researchers have published

numerous analyses of the upper extremity. Each researcher has described a slightly different method to analyze the motion of the upper limb.

Panjabi and White (1971) described a method of three-dimensional mathematical analysis of the rotation of the spine, which may be adapted to provide a general three-dimensional analysis procedure. They used Euler's method and a modified vector method for their analysis of the spine. When they employed actual experimental data, Euler's method gave unreasonable results or none at all. Despite this failure, they noted that this experimental technique and mathematical analysis could be "productively applied to other joints, especially some of the more complex ones like the shoulder, hip, and ankle" (1971).

Ramey and Nicodemus (1977) noted that many biomechanists have reported angular kinematic values based on a single plane analysis which have limited application for typical non-planar movements in most sports. They have described a procedure for transforming reference frames for each type of rotation which occurred in the segment, so that the angular velocity can be reported in terms of the components of angular velocity around each one of the three primary axes: X, Y, and Z.

Miller (1970) calculated the angular momentum of a springboard diver based on the whole body angular velocity and moment of inertia obtained from the quasi-rigid posture frame. This method, however, is usable only in 2D motion where all body segments rotate about one common axis. Also, Ramey (1973) used the information obtained from the force platform (combined with the cinematographical analysis) to calculate angular momentum of a long jumper based on the torque-time curve.

A more general and comprehensive way to calculate the transverse and longitudinal angular velocity of a rigid body is the use of Eulerian angles. Any 3D angular motion of a segment can be expressed in terms of three successive rotations along three contemporary axes. The angular velocity of a segment can be expressed as a function of three Eulerian angles and their first time-derivatives (Yeadon, 1990). The angular velocity of a rigid segment can also be obtained from the rotational transformation matrix using the inertial reference frame and the non-inertial reference frame fixed to the segment (Ramey & Yang, 1981).

Pearson, McGinley, and Butzel (1963) described the method of analysis of the motion of the upper extremity in the X-Y plane. They regarded the upper limb as consisting

of two segments - the arm and the forearm plus hand. They calculated angular values for the displacements of each of these segments throughout a particular motion. The intent of this model was to compute the forces and torques at the shoulder and elbow joints and to derive an understanding of the muscle actions involved as well as the amount of strain at these joints.

Morrey and Chao (1976) described a method of measuring the passive motion of the elbow joint using a three dimensional vector analysis technique. They expressed the rotational motion of the forearm with respect to the humerus in terms of the Eulerian angles which uniquely describe the components of three-dimensional elbow motion. The first angle is the flexion-extension angle; the second angle is the carrying angle (abduction and adduction at the elbow); and the third angle is that of axial rotation.

Ayoub, Walvekar, and Petrino (1974) also developed a biomechanical model for 3D analysis of upper extremity motion. They used the basic equations of Newtonian mechanics to calculate the force and moments at the joint and used the Euler angles to specify a body segment orientation in space at any time during the motion, relative to an X, Y, and Z coordinate system. They could then express the angular velocity and acceleration of the segment

as a function of the first and second derivatives of the segment's Euler angles.

Quantitative Analysis

Ball Velocity

Scholars have disputed over the velocity of the ball resulting from the windmill delivery in softball pitching. Hay (1978), Miller and Shay (1964), and Sullivan (1965) noted that velocities up to 98.8 mile/h (145 feet/s) have been reported for some of the best softball pitchers. But Miller and Shay (1964) failed to substantiate these findings in a study involving nine male pitchers from top-level leagues in the New England area who pitched balls at speeds averaging approximately 60 mile/h (88 feet/s). Bune (1972) also reported that an average curve ball in major league baseball travels at 84 feet/s (57 mile/h), 10 feet/s (6.8 mile/h) less than a fast ball. In view of this and other evidence presented, it seems questionable whether a pitcher throwing a softball with an underhand delivery can attain ball velocities similar to those achieved by a few of the best major league baseball pitchers.

Several researchers have conducted studies involving highly skilled male windmill pitchers (James, 1971; Alexander, 1978; Guenzler, 1979; Seevers, 1986). James (1971) found that three subjects pitched the drop ball at an

average speed of 86.7 ft/s (59.1 mile/h) and the rise ball at an average speed of 85.1 ft/s (58 mile/h). Alexander (1978) found that average fast ball velocity of each subject was 29.68 m/s (66.40 mile/h) and 32.46 m/s (72.62 mile/h), respectively. Guenzler (1979) reported that five subjects pitched the drop ball at an average speed of 100.3 ft/s (68.4 mile/h) while they threw the rise ball at an average speed of 96.9 ft/s (66.1 mile/h). Seevers (1986) reported that the average fast ball velocity was 66 mile/h in his study. James concluded that "the slower velocity rise ball was probably due to the greater amount of energy used to impart spin on the ball to make it rise" (p. 30). Also, Guenzler agreed that an average drop ball is released with more initial velocity than a typical rise ball.

Also, several researchers have conducted studies involving highly skilled female windmill pitchers (Alexander, 1978; Bridges, 1982; Kinne, 1985; Werner, 1994a). Alexander (1978) found that average fast ball velocity of two subjects was 24.46 m/s (54.72 mile/h) and 24.94 m/s (55.79 mile/h), respectively. Bridges (1982) reported that the ball velocity for the fast, curve, and rise ball was 73.12 mile/h, 60.66 mile/h, and 58.46 mile/h, respectively. Kinne (1985) found that the mean for the velocity of the pitch at release in fast, rise, and drop

ball was 85.81 ft/s (58.51 mile/h), 81.60 ft/s (55.64 mile/h), and 80.20 ft/s (54.69 mile/h), respectively. Werner (1994a) reported that the average fast ball velocity at release for the eight pitchers was 58 mile/h, with a range of 53 mile/h to 62 mile/h.

Stride Length

Studies which deal with stride length and its effect upon a windmill pitcher's performance are also relevant. The length of the "ideal" stride as presented by various authors depends greatly on the pitcher's height. Several investigators have conducted studies involving highly skilled male windmill pitchers (Alexander, 1978; Guenzler, 1979; Seevers, 1986). Alexander (1978) measured the stride lengths of two pitchers and converted these lengths to percentages of the subjects' standing heights. In this study, the percentages were reported to be 52.79% and 80.90%. Guenzler (1979) reported that stride length ranged between 60% to 80% of the pitchers' heights. Seevers (1986) reported an average stride length of 4.68 feet. The prediction of stride length in Alexander's and Guenzler's investigations were quite high. That means good performers take longer steps than those who are less skilled and that the length of the step distinguishes good from poor performers (Cooper, Adrian, & Glassow, 1982). Hofstetter

(1980a) stated that a short stride may reduce a pitcher's ability to rotate the hips and shoulders and may cause undue strain on the pitching arm.

Researchers also have conducted studies involving highly skilled female windmill pitchers (Zollinger, 1973; Alexander, 1978; Bridges, 1982; Kinne, 1985; Werner, 1994a). Zollinger (1973) reported that the average stride length of one windmill pitcher was 69% of the subject's standing height. Alexander (1978) found stride lengths to be 61.97% and 68.22% of two subjects' standing heights, respectively. Bridges (1982) found that the stride length for fast, curve, and rise ball was 83%, 82%, and 85% of the subject's standing height, respectively. Kinne (1985) found that the mean for stride length was 59.87% for the fast ball and 59.99% for the rise ball; the standard deviation was 5.75% for the fast ball and 6.18% for the rise ball. Werner (1994a) reported that the average stride length compared to body height was 73% and ranged from 56% to 86%.

Torques and Forces in the Upper Extremity

Zollinger (1973) found that the velocity of a pitch was directly related to the magnitude of the torque about the shoulder during the arm's downswing and the amount of torque about the wrist at release. An additional torque about the radio-ulnar joint contributed to the spin of the softball.

The author claimed that this torque did not affect the ball's velocity. She reported that the torque about the shoulder was 109.12 foot-pounds and the torque about the wrist was 38.74 foot-pounds. In other words, the torque about the shoulder was 2.8 times greater than that about the wrist.

Kinne (1985) revealed that the mean torque about the shoulder during the arm's downswing was 1287.1b-ft (88.19 ft-pound) for the fast ball and 1338.48 lb-ft (91.72 ft-pound) for the rise ball.

Alexander (1978) found that the large negative moment at the shoulder joint occurs at a point 0.03 to 0.04 seconds prior to the release of the ball. This negative moment produced an accompanying negative moment at the elbow and wrist joints, even though both of these joints were flexing at this point in the pitch. These results indicated that the shoulder extensors were acting eccentrically as a brake to slow down the flexion of the upper arm at the shoulder joint. This fact is especially insightful because the major force producing muscles in this technique were thought to act strongly up to the point of release.

Contribution of Various Joint Actions

Only two studies were found which have discussed the contribution that various joint actions make to the velocity

of the ball at release from a windmill pitch. Cooper et al. (1988) reported that the contribution of the rotation of joint segments (expressed in percentages), using the sum of the linear velocities, are as follows: hip, 14.3%; spine, 7.9%; shoulder, 45.3%; wrist, 32.4%. Gowitzke and Milner (1980) found that pelvic rotation made a 16.4% contribution to the velocity of the pitch; spinal rotation, 9.9%; shoulder flexion, 36.79%; wrist flexion, 25.6%; and sternoclavicular protraction, 12.10%. In both studies, shoulder flexion appeared to be the major contributor to the velocity of the softball at release.

Ground Reaction Forces

Only one study, conducted by Alexander (1978), was found which collected data on ground reaction in softball pitching. She found that the force curves produced by her two subjects were quite different from each other. One subject reached peak forward forces much earlier than the other subject. In fact, one subject exerted forward force in a negative direction at the time of the release of the ball. The vertical forces were somewhat similar in both subjects. The peak in the vertical ground reaction forces occurred at almost exactly the same instant in the delivery for each of the subjects. This point was approximately .04 to .05 seconds prior to the release of the ball. Alexander

was a pioneer in the study of ground reaction force but her data are limited and her study is too generalized. A more comprehensive study of the ground reaction force for different styles of pitching and its impact on ball velocity and pitching motion is still needed.

CHAPTER III

METHODS

The purpose of this study was to identify the relationship of selected kinematic and kinetic variables with the windmill style of softball delivery for the fast and change-up pitches. The investigation procedures were grouped under the following headings: (1) subjects, (2) videography methods, (3) video analysis, (4) data analysis, and (5) statistical analysis.

Subjects

In order to select the subjects for this study, coaches of different schools were contacted to obtain information about the pitchers. Subsequently, a questionnaire was distributed to obtain data regarding the pitcher's performance. Pitchers who had a good pitching record based on earned run average (ERA) and were free of injury were approached to volunteer for this study. The volunteers were 18 highly skilled female pitchers who participated in softball leagues. Of the 18 subjects selected, six participated at the middle school level, six at the high school level, and six at the college level. General information about the subjects is summarized in Appendix B1.

All subjects selected were right-handed windmill pitchers. This provided convenience for data analysis and interpretation. Prior to videotaping the pitching patterns of the subjects, each volunteer completed a questionnaire and an informed consent form in compliance with requirements approved by the Michigan State University Committee for Research Involving Human Subjects. The investigator recorded the subjects' height and weight and other essential data (see Appendix A). Before pitching, the subjects were provided with a 10-minute warm up period.

Videography Methods

The videography methods used to collect data in this study were divided into two categories: (a) videotape equipment and (b) videotape procedures.

Videotape Equipment

Video Cameras

Two video cameras, Panasonic S-VHS AG-455P video camcorders, were placed on tripods and located as shown in Figure 3.1. Camera 1 was placed on the throwing arm side and behind the pitcher. This camera was approximately 11m from the center of the force platform and about 1.2m above the ground. Camera 2, located in front and to the throwing arm side of pitcher, was about 10m from the center of the force platform and approximately 1.6m above the ground.

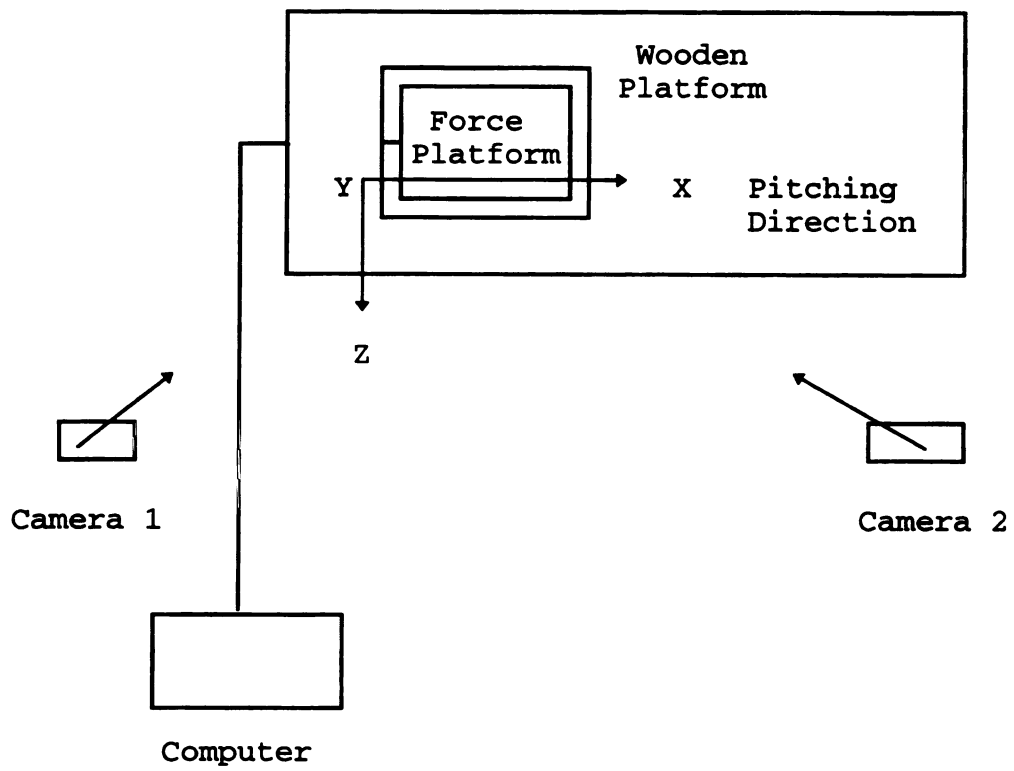


Figure 3.1 Camera settings for the videotaping.

The field rate of each video camera was 60 Hz. Their mechanical shutters were set to 1/1000s to minimize the occurrence of image blur.

Range Poles

Range poles were used to obtain the 3-D coordinates of the control points required for the direct linear transformation (DLT) method used in 3D analysis. The set was composed of four range poles. The length of each pole was 240cm. Eight control points were marked on each pole with the distance between adjacent points being 30cm. The control points were numbered beginning at the bottom point of each pole. The range poles were set vertically by using a rod level. The equipment setting for the range pole survey and the global reference frame used in this study are presented in Figure 3.2. The range poles were placed in a rectangle around the pitching activity area. The distance between pole 1 and pole 2 and pole 3 and pole 4 was 200cm. The distance between pole 1 and pole 3 and pole 2 and pole 4 was 250cm. The trials of windmill softball pitching were encompassed within the volume established by the range poles.

Force Platform

An AMTI force platform measured three orthogonal components of the resultant ground-reaction force (X axis is

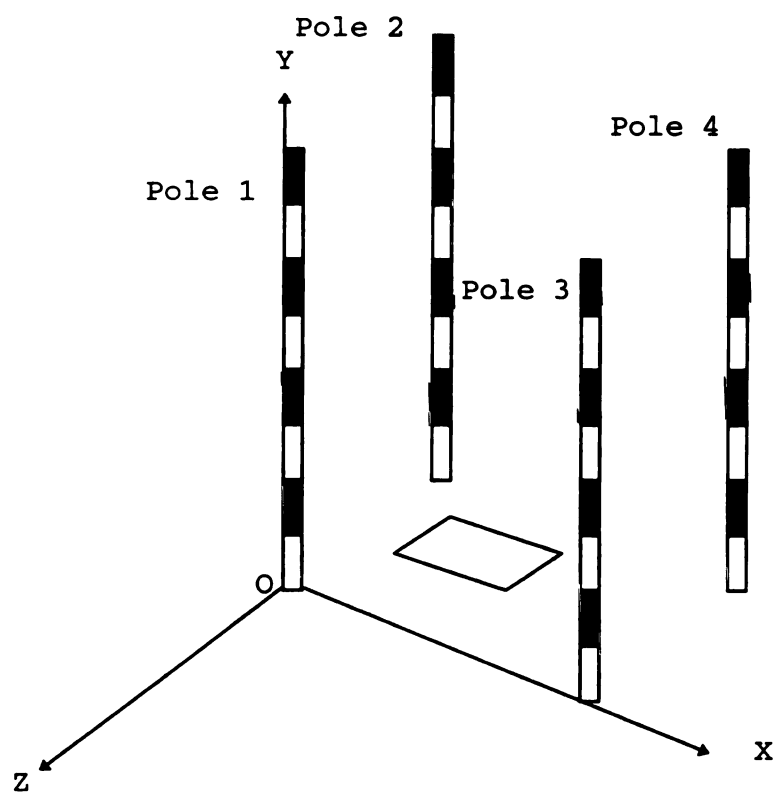


Figure 3.2 Equipment settings for the range pole.

parallel with a line connecting the center of the pitching rubber and home plate, Y axis is vertical, and Z axis is in line with the long axis of the pitching rubber). The force platform was leveled on the ground with a metal mounting frame which rested on the hard surface of a tennis court. Force platform recordings were obtained and stored by an Ariel Performance Analysis System (APAS). Force and videographic recordings were synchronized by matching a signal of a ball impacting the force platform immediately prior to each recorded pitch.

Videotape Procedures

All 18 subjects were filmed in an outdoor setting on the same day. The subjects wore short sleeve shirts, short pants and exercise shoes. Black adhesive disks, with a diameter 3cm, were placed on the shoulder, elbow, and wrist joints of the pitching arm after a subject warmed by stretching and taking several practice pitches. These targets were used as guides in the video digitization process.

For the video records, the subjects performed three trials of two different types of windmill pitches (fast and change-up) using an official softball (12-inch circumference, 6-ounce weight). The pitchers placed their right foot on the force platform, which served as the

pitching rubber. After driving off the force platform, they stepped with their left foot forward onto the wooden platform which surrounded the force platform and was of the same height. The selection of the best fast and change-up pitch was based first on the accuracy of the ball in the strike zone and secondly on the highest velocity recorded for the strike pitch. A home plate and vertical rectangular strike zone were used to guide the accuracy of the pitchers. For efficient management of data only one trial of each type of pitch for each subject of was used for analysis. Moreover, the velocity and accuracy of each subjects' performance for both styles of pitching remained consistent. Therefore, it was reasonable to select the best performance for this study.

Video Analysis

The procedures used to analyze the video records and to determine the smoothed 3D coordinates of the body landmarks throughout the pitch are described in this section. This section is divided into five parts: (1) DLT techniques, (2) frame grabbing, (3) digitizing, (4) synchronization, and (5) calculation of the 3D landmark data.

DLT Techniques

The method of transforming two or more 2D images of the same spacial points into 3D coordinates is known as direct

linear transformation (DLT). Abdel-Aziz and Karara (1975) developed the DLT method. It has been described in detail by Walton (1981). In fulfilling the requirements of the DLT method, range poles, with known 3D coordinates, were placed around the activity area (see Figure 3.2) and videotaped simultaneously by two cameras prior to videotaping the subjects' performances. The range poles were then removed, and the actual trials of the fast and change-up pitches were videotaped. The two 2D video images of the 32 known 3D coordinates (control points), located on the range poles, were digitized. These digitized coordinates, together with the known coordinates of the control points, were used to solve a set of simultaneous linear equations which produced the transformation (3D coordinates).

Frame Grabbing

The first step for analysis, after the video records were obtained, was to capture selected video image sequences via the APAS system for subsequent digitization. Electronic frame grabbing provides a method of transforming an image displayed on a video monitor into a digital image which can be manipulated by computer software. Video images of each field of the pitching sequence were captured by a computer and stored in its memory. The image sequences could be

retrieved from computer's memory and displayed. If a part of the image was too small or blurred, the size of this area was enhanced in order to more accurately determine a particular joint locations.

Digitizing

The Ariel Performance Analysis System (APAS) was used to digitize the control points and the body landmarks. First, the 32 control points located on the range poles were digitized. Second, the 22 body landmarks located on the subject, the center of the ball, and the digitizing origin located on the right edge of the force platform were digitized in all fields of each selected pitching sequence. The origin was digitized before the body landmarks in each field of each selected sequence. Subsequently, all digitized points were expressed as real world coordinates relative to the origin. This process was followed for two reasons: (1) to calculate 3D coordinates using the DLT method and (2) to correct the drifting of images associated with vibration of the camera during the video session and with video image distortion. Every image field recorded was digitized at least once. In order to make the data reliable, digitization of the same pitching motion was done twice and the results were significantly correlated ($r = .95$). Also, to reduce digitization error, when necessary,

digitization of selected points were done several times and average values used for analysis. In order to prevent the loss of the complete field of the actual performance five fields prior to start of the pitching motion and five fields after ball release were included in the digitizing.

Synchronization

Before the actual pitch was thrown, a ball was dropped on the force platform. This contact point was used for synchronizing each camera view and also the film and force platform data. At this point of contact, the force platform got the impact signal from the ball. The time for each field in each view was adjusted relative to the synchronizing process so that synchronizing occurred at the same absolute time. The zero-time fields of the camera views were matched, and the interpolation of the digitized coordinates was performed based on this time alignment starting from the zero-time. The video coordinate-time data obtained from each camera were fitted by the cubic spline function. The interpolation time interval for this study was 0.017 second (60Hz).

Calculation of 3D Coordinates of the Body Landmark

The DLT method was used to determine the raw 3D coordinates. The DLT parameters of the cameras and the interpolated values obtained from the digitized coordinates

of the landmarks from the video of each camera were then used to compute the 3D coordinates of the body landmarks. The coordinates were initially expressed in terms of reference frame O, the reference frame defined by the DLT control object (see Figure 3.3). The 3D coordinates were then transformed to O (with axes X, Y, and Z), a right-handed orthogonal inertial reference frame relevant to the softball pitch. Vector Z was horizontal and directed along the rear edge of the force platform; X was horizontal and directed toward home plate; Y was vertical.

Data Analysis

The data collected for this study, associated with a successful windmill style softball pitch of each style, were analyzed under the following five classification: (1) temporal analysis, (2) model of the body, (3) pitching parameters, (4) kinematic analysis, and (5) kinetic analysis. The analysis in this study was based on the examination of data within each group and comparison among the three groups. In order to represent a pattern within a group, a single subject who demonstrated the average value of the group's performance in terms of accuracy and velocity was selected. When comparing results among the three groups, the mean value of each group was evaluated.

Temporal Analysis

The pitching motion was divided into three major movement phases: presentation, execution, and recovery. In order to analyze the temporal periods and to aid in the interpretation of the results among the three subject groups, each selected trial was analyzed to determine the sequence of actions and the actual time elapsed between events. The procedure involved counting fields of video to determine the elapsed time between the following events: (1) the stride foot takeoff from the force platform to ball release, (2) highest point of the pitching arm to ball release, and (3) stride foot contact with wooden platform to ball release.

Model of the Body

The human body, modeled as fourteen rigid body segments (head, trunk, arms, forearms, hands, thighs, shanks, and feet), was defined by 22 body points. The nose point was the imaginary joint on the head used to identify the direction of the face. The suprasternale was defined as a point halfway between the chest and the back and the level of the suprasternal notch in middle shoulder. The body points are listed in Table 3.1.

Table 3.1 Body Points of Human Body Model

1. TOP OF HEAD (TH)	12. LEFT HAND (LD)
2. CHIN/NECK (CN)	13. RIGHT HIP (RH)
3. NOSE (NO)	14. RIGHT KNEE (RK)
4. SUPRASTERNAL (SU)	15. RIGHT ANKLE (RA)
5. RIGHT SHOULDER (RS)	16. RIGHT HEEL (RL)
6. RIGHT ELBOW (RE)	17. RIGHT TOE (RT)
7. RIGHT WRIST (RW)	18. LEFT HIP (LH)
8. RIGHT HAND (RD)	19. LEFT KNEE (LK)
9. LEFT SHOULDER (LS)	20. LEFT ANKLE (LA)
10. LEFT ELBOW (LE)	21. LEFT HEEL (LL)
11. LEFT WRIST (LW)	22. LEFT TOE (LT)

Body segment parameters are critical factors in biomechanical research. They are used to provide accurate estimates of relative masses, centers of gravity, and radii of gyration of individual body segments. These values have been primarily derived from cadavers. As noted by Plagenhoef (1973), the anatomical data presented by Dempster (1955) has been the most widely used and modifications of his data may be used to estimate body proportions in the

living as well. The values of body segment parameters used in the current study were taken from Dempster's (1955) cadaver data and from Clauser et al. (1969). The moment of inertia values of each segment were taken from Whitsett (1963). The moment of inertia values of each segment about its transverse and longitudinal axes were I_t and I_l , respectively.

Pitching Parameters

For each of the pitches videotaped, the velocity of the ball in the six fields following release was calculated. Another important factor in the softball pitch was the length of the stride taken during the pitch. Stride lengths were compared between pitchers of different sizes by reporting them as a percentage of their standing height. The stride length for the pitches of each subject was calculated as the distance from the toe of the pivot foot (right foot) to the heel of stride foot (left foot).

Kinematic Analysis

To investigate the pattern of pitching motion and to aid in the interpretation of these data, various kinematic parameters were calculated.

Coordinate Systems

In order to establish a mathematically workable model, three Cartesian coordinate systems were established as shown

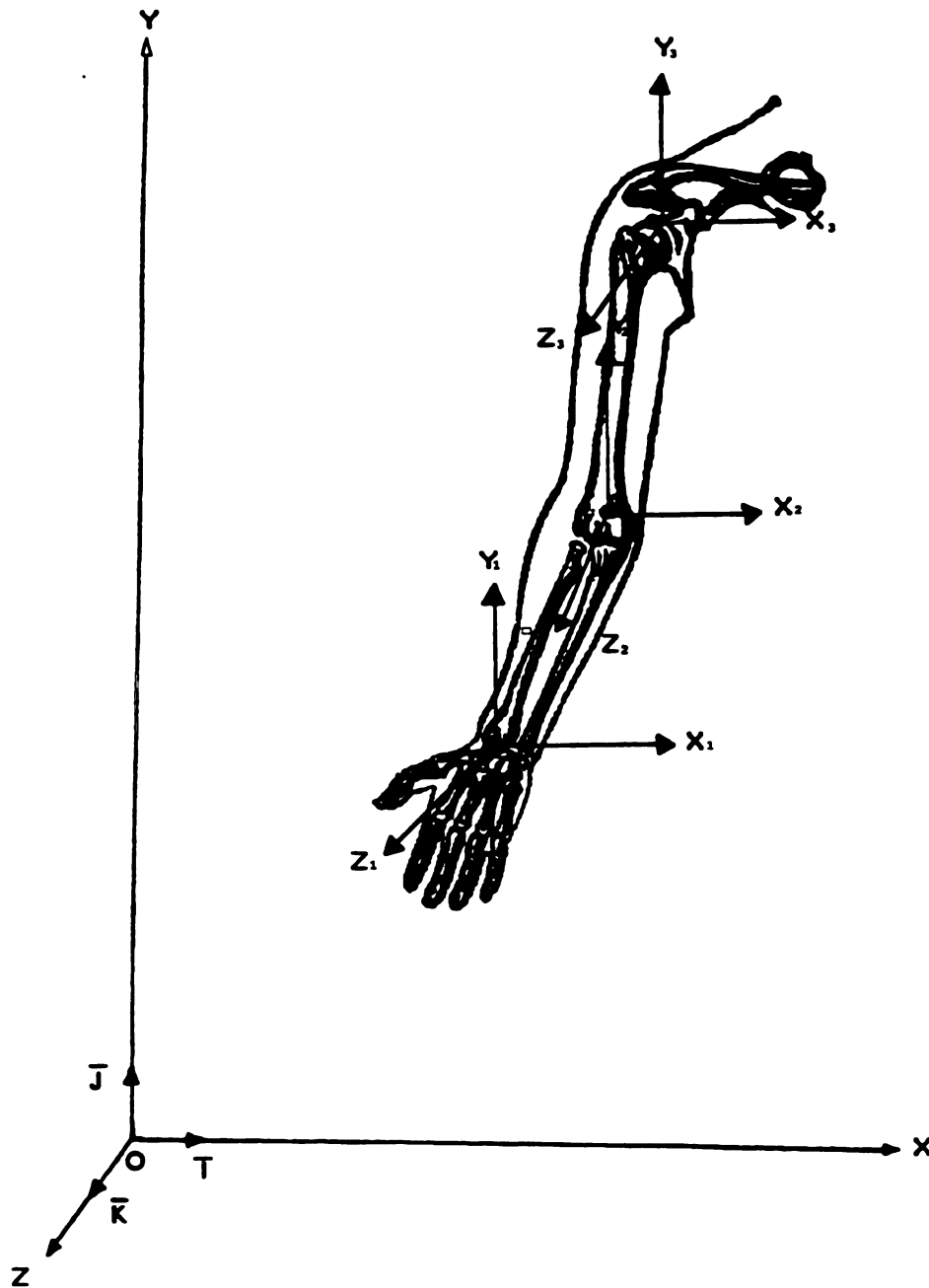


Figure 3.3 Mechanical model of the throwing arm.

in Figure 3.3. A segmental axis system was established for each body segment. These anatomically based axis systems are fixed in these joints (wrist, elbow, and shoulder), O_i ($i= 1$ to 3), and move with them. These coordinate systems have been used to define the locations and orientations of the joints.

Axis System

In each bone the coordinates of bony landmarks are used to construct a right-handed orthogonal anatomically based reference frame for the right upper extremity. The unique specification of anatomical coordinate systems requires a minimum of three non collinear points which are defined with respect to surface landmarks associated with each segment. As a general procedure, the direction of one axis (or vector) was defined directed line from one point to another. In order to compute the force and torque, two non-inertial reference frames were defined. These reference frames, O_2 and O_3 , defined at the elbow and shoulder, were oriented so that their axes coincided with the principal axes of the forearm and arm. The Z axis for the forearm was defined from the elbow to the wrist. The X axis was then defined as the cross product of the vector from the elbow to the shoulder with the forearm vector **Z**. The Y Axis was then

defined as the cross product of the vector **Z** with **X**. The Z axis for the arm was defined as the vector from the shoulder to the elbow. The X axis was then defined by the cross product of the vector from suprasternale to the mid-hip point with **Z**. The Y axis was then defined as the cross product of **Z** with **X**. This approach is similar to those found in the study by Feltner and Dapena (1986).

Transformation Matrix

The transformation matrix, to convert between the distal and proximal coordinate systems, used the Eulerian angles to describe the orientation of each segment (McGill & King, 1989). In order to define joint motion, O_{xyz} was defined as a laboratory-based, right-handed, orthogonal, inertial reference frame with unit vectors of the shoulder, i.e. coordinate system $O_{x_1y_1z_1}$ is defined as the inertial coordinate system, O_{xyz} . Once the spatial locations of the coordinates systems were known, the relative joint motion could be calculated following the classical kinematic theory. The transformation from the fixed coordinate system (I,J,K) to the moving coordinate system (i,j,k) was obtained by three successive rotations performed in a specific order (see Figure 3.4). The sequence starts by rotating the initial system of axes through an angle ϕ

about the K axis which resulted in an intermediary system (i', j', k') . The second rotation was through an angle θ about the j' axis which produced an intermediary system (i'', j'', z'') . Finally, the third rotation was through an angle ψ about the i'' axis. This gave the final orientation of the moving system (i, j, k) relative to the fixed system (I, J, K) .

A rotational transformation matrix from one reference frame to another can be expressed as the product of three sequential elementary rotation matrices. The elements of the transformation matrix are shown in Figure 3.4.

$$[T_\phi] = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3.1)$$

$$[T_\theta] = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \quad (3.2)$$

$$[T_\psi] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & \sin\psi \\ 0 & -\sin\psi & \cos\psi \end{bmatrix}. \quad (3.3)$$

The three consecutive rotations with respect to the ϕ, θ and ψ axes are represented by $[T_\phi]$, $[T_\theta]$, and $[T_\psi]$ respectively. The final transformation matrix between the distal and proximal frames can then be written as:

$$[T_1] = [T_\psi][T_\theta][T_\phi] \quad (3.4)$$

Using these Eulerian angles, the transformation matrix $[T_1]$ of the upper arm segment relative to the inertial frame is $[T_1] = [T_\psi][T_\theta][T_\phi]$, so that components of a vector are

$$\begin{bmatrix} c\theta c\phi & c\theta s\phi & -s\theta \\ -c\psi s\phi + s\psi s\theta c\phi & c\psi c\phi + s\psi s\theta s\phi & s\psi c\theta \\ s\phi s\psi + c\psi s\theta c\phi & -s\psi c\phi + c\psi s\theta s\phi & c\psi c\theta \end{bmatrix} \quad (3.5)$$

in which

s = sine and

c = cosine.

This transformation equation was utilized in the kinetic analysis to express the vectors in the appropriate coordinate system derived from the free body diagram.

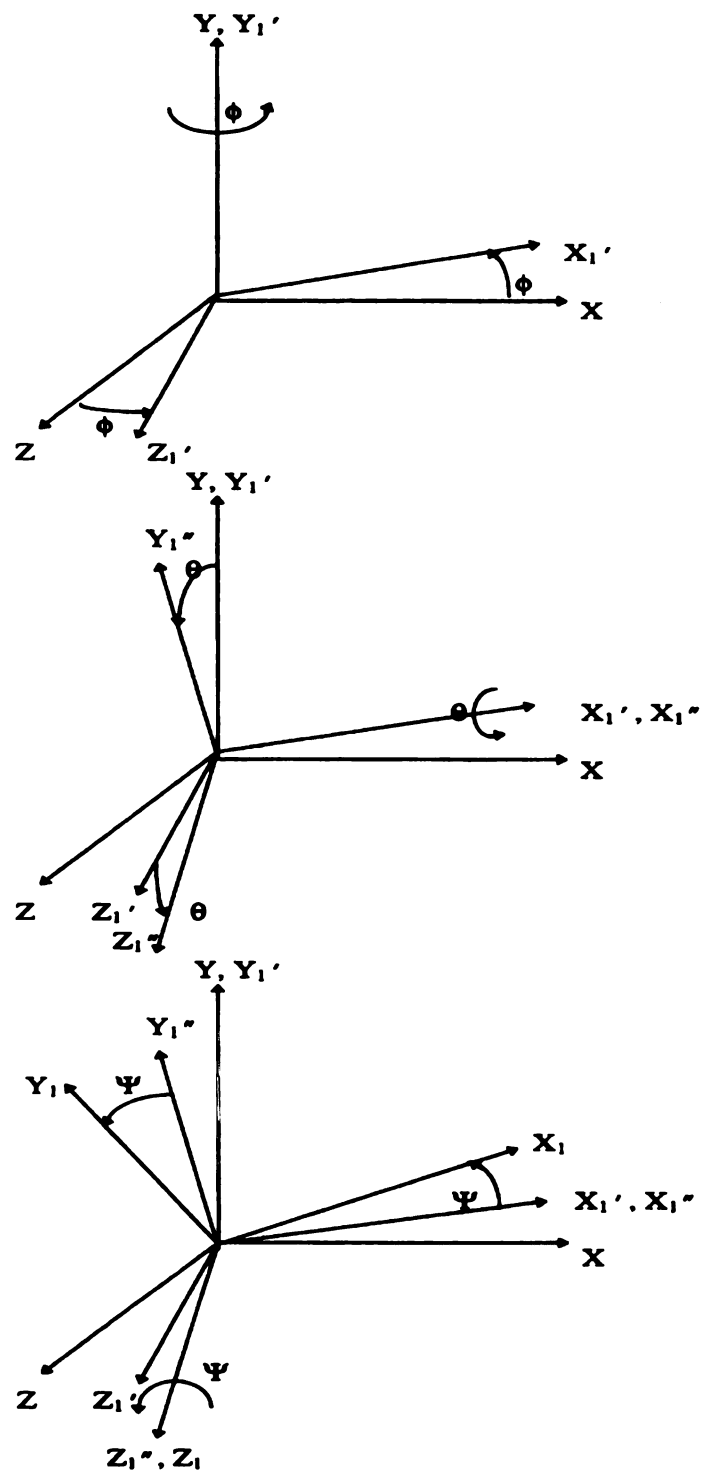


Figure 3.4 Eulerian angles in rigid body.

Contributing Factors to Ball Velocity

The velocity of the ball after release is determined primarily by the velocity of the hand just before it releases the ball. The velocity of the ball (V_B) can be considered to be the sum of the velocities of the center of mass(c.m.) of the whole body (V_G) and the velocity of the hand relative to the c.m. of the whole body ($V_{HD/G}$):

$$V_B = V_G + V_{HD/G} \quad (3.6a)$$

This equation can be expanded.

$$V_B = V_G + V_{HP/G} + V_{TK/HP} + V_{SH/TK} + V_{ELB/SH} + V_{WR/ELB} + V_{HD/WR} \quad (3.6b)$$

in which

$V_{HP/G}$ = the velocity of the c.m. of the thigh

relative to the c.m. of the whole body,

$V_{TK/HP}$ = the trunk relative to the thigh,

$V_{SH/TK}$ = the shoulder relative to the c.m. of the trunk,

$V_{ELB/SH}$ = the elbow relative to the shoulder,

$V_{WR/ELB}$ = the wrist relative the elbow,

$V_{HD/WR}$ = the c.m. of the hand relative to the wrist.

The velocity of the distal endpoint of a body segment relative to the proximal one ($V_{d/pi}$) can be expressed by the following general equation:

$$V_{d/pi} = \omega_{i/GR} \times r_{d/pi} + (V_{d/pi})_{m/s}$$

in which

$\omega_{i/GR} \times r_{d/pi}$ = the tangential component of the relative velocity,

$\omega_{i/GR}$ = the angular velocity of the segment relative to ground,

$r_{d/pi}$ = the location vector of the distal endpoint relative to the proximal endpoint, and

$(V_{d/pi})_{m/s}$ = the radial component of the the relative velocity.

The tangential component of the velocity is associated with the rotation of the segment; the radial component is associated with changes in the distance between the two endpoints, and, thus, it implies non-rigidity of the

segment. Therefore, the radial component was not considered in this study. This equation developed by Chung (1988) was applied to the hand, forearm, arm, trunk, and thigh.

Angular Velocity

The angular velocity of the moving system with respect to the fixed system may be expressed as the vectorial sum of the three partial angular velocities corresponding respectively to the flexion-extension, abduction-adduction, and the internal-external rotation of the shoulder (Ramey & Yang, 1981). The angular velocity is

$$\omega = \dot{\phi} K + \dot{\theta} j' + \dot{\psi} i'' . \quad (3.7)$$

Since the vector components obtained for ω in equation 3.7 are not orthogonal, the unit vectors K , j' , and i'' will be resolved into components along the unit vectors (i,j,k) of the rotating axes. The unit vector K is resolved into components along the x,y,z axes by three successive rotations, ϕ , θ , and ψ thus

$$K = -\sin(\theta)i + \cos(\theta)\sin(\psi)j + \cos(\theta)\cos(\psi)k. \quad (3.8)$$

The unit vector j' is resolved into components along the x , y , and z axes by two rotations; θ and ψ , so

$$j' = \cos(\psi)j - \sin(\psi)k. \quad (3.9)$$

Similarly, the unit vector i'' , transformed into the x , y , and z system by a rotation, ψ , about x'' axes, will not change the unit vector in the x -direction, so

$$i'' = i. \quad (3.10)$$

Substituting equations 3.8, 3.9, and 3.10 into equation 3.7, the angular velocity with respect to the rotating axes in terms of the Eulerian angles is

$$\begin{aligned} \omega = & \left[\dot{\psi} - \dot{\phi} \sin(\theta) \right] i + \left[\dot{\theta} \cos(\psi) + \dot{\phi} \cos(\theta) \sin(\psi) \right] j \\ & + \left[\dot{\phi} \cos(\theta) \cos(\psi) - \dot{\theta} \sin(\psi) \right] k. \end{aligned} \quad (3.11)$$

The angular acceleration components; $\dot{\omega}_x$, $\dot{\omega}_y$, and $\dot{\omega}_z$; can be calculated directly from the angular velocity components, ω_x , ω_y , and ω_z . After taking their time derivatives, the

angular acceleration components with respect to the rotation axes become:

$$\alpha = \alpha_x i + \alpha_y j + \alpha_z k. \quad (3.12)$$

The term, α_x , α_y , α_z , may be expressed as follow:

$$\alpha_x = \ddot{\psi} - \ddot{\phi} \sin(\theta) + \dot{\phi} \dot{\theta} \cos(\theta), \quad (3.13)$$

$$\begin{aligned} \alpha_y = & \ddot{\theta} \cos(\psi) - \ddot{\theta} \dot{\psi} \sin(\psi) + \ddot{\phi} \cos(\theta) \sin(\psi) \\ & - \dot{\phi} \dot{\theta} \sin(\theta) \sin(\psi) + \dot{\phi} \dot{\psi} \cos(\theta) \cos(\psi), \text{ and } (3.14) \end{aligned}$$

$$\begin{aligned} \alpha_z = & \ddot{\phi} \cos(\theta) \cos(\psi) - \ddot{\phi} \dot{\theta} \sin(\theta) \cos(\psi) \\ & - \dot{\phi} \dot{\psi} \cos(\theta) \sin(\psi) - \ddot{\theta} \sin(\psi) - \ddot{\theta} \dot{\psi} \cos(\psi). \end{aligned} \quad (3.15)$$

Kinetic Analysis

The kinetic analysis was used to calculate the forces and torques at the shoulder and elbow for each pitch. The procedures used for this calculation are described as follows.

Moment of Inertia

An inertia matrix is associated with every point of a rigid body. To reach the inertia matrix, it is necessary to rotate and translate the centroidal principal moments of

inertia. The moment of inertia of a body segment with respect to orthogonal axes aligned with the anatomical (local) axes and having a common origin with the centroidal principal moments of inertia may be determined by the following formula:

$$[I_c] = [D] [I_p] [D]^T \quad (3.16)$$

where

$[I_c]$ = centroidal inertia tensor in the local reference frame,

$[D]$ = matrix of direction cosines of the centroidal principal inertial axes with respect to the local axes, and

$[I_p]$ = centroidal principal inertial tensor.

Further, there exists a relation between the inertia matrix

$[I_c]$ about the local centroidal axes and the moment of

inertia $[I]$ about a set of axes parallel to the local

centroidal axes according to the parallel-axis theorem (Nigg

& Herzog, 1994). This relationship is expressed by the

equation:

$$[I] = [I_c] + m \cdot \begin{bmatrix} b^2+c^2 & -ab & -ac \\ -ab & a^2+c^2 & -bc \\ -ac & -bc & a^2+b^2 \end{bmatrix} \quad (3.17)$$

where (a,b,c) is the location of the center of mass with respect to the parallel coordinate system. This relationship is the well known parallel-axis and parallel-plane theorems for the moments of inertia.

Force and Torque

In using the procedures of Newtonian analysis, the forces and torques which act on each separate rigid element must be accounted for and included in the associated free-body diagram. The joint constraint forces acting on the segment at the proximal and distal anatomical joints due to the presence of adjacent segments must be included (Anderws, 1974). A general diagram of a typical anatomical segment is depicted in Figure 3.3. The pitching arm was modeled as having three segments (arm, forearm, and hand with ball). The dynamical equilibrium of the free body requires that in deriving the equations governing the forced motion of the moving body segments to have the following terms

$$\Sigma F = F_P + F_D + mg \quad (3.18)$$

$$\Sigma T = T_P + T_D + L_D \times F_D + cg \times mg \quad (3.19)$$

where

F_P and T_P = intersegmental force and torque of
the proximal joint about which rotation
occurs and

F_D , T_D , and L_D = force and torque and location of the
distal joint about which the next body segment
rotates. These terms provide for the coupling
of force and torque from distal to proximal
body segments.

m = mass.

cg = position vector of the center of mass from the
point of body segment rotation.

These equations are written with the vectors expressed in the coordinates of the local coordinate system located at the assumed center of rotation of the joint at the proximal end of the bone. The force and torque vectors for the distal joint must be transformed into the proximal coordinate system, and the location of the distal center of rotation must also be translated into this system.

Statistical Analysis Procedures

One way ANOVA with repeated measures using SPSS statistical package (version 7.0) was applied to compare the three groups and also the two styles of pitching. All numerical data presented in the text are the mean and standard deviation values of the particular measure, unless explicitly stated otherwise.

In order to show the distribution of the values, boxplot graphics were used. These graphics show the mean value of the groups and the outlying values of some subjects. In terms of statistical analysis, the outlying values were excluded because the number of the subjects selected for this study was too small to make such calculations. However, the outlying values were included in calculating the mean values. They may have affected the mean value of a group but did not affect the mean group differences.

CHAPTER IV

RESULTS

The presentation of the results of the analysis of the windmill pitch in softball is subdivided into the following topics: (1) temporal data, (2) pitching parameters, (3) kinematics, and (4) kinetics.

Temporal Data

The temporal data of the softball pitch are reported in Appendix B2. The temporal analysis of the pitch is based upon four events (see Figure 1.1): stride foot takeoff from force platform, highest point of the pitching arm, stride foot contact with wood frame, and ball release. These four events determine three intervals: A-stride foot takeoff from force platform to ball release, B-highest point of pitching arm to ball release, and C-stride foot contact with wooden frame to ball release. The mean times for the fast and change-up pitches for the middle school subjects were 0.538 s and 0.555 s for interval A, 0.170 s and 0.198 s for interval B, and 0.142 s and 0.147 s for interval C, respectively. The mean times for the fast and change-up pitches for the high school subjects were 0.513 s and 0.559

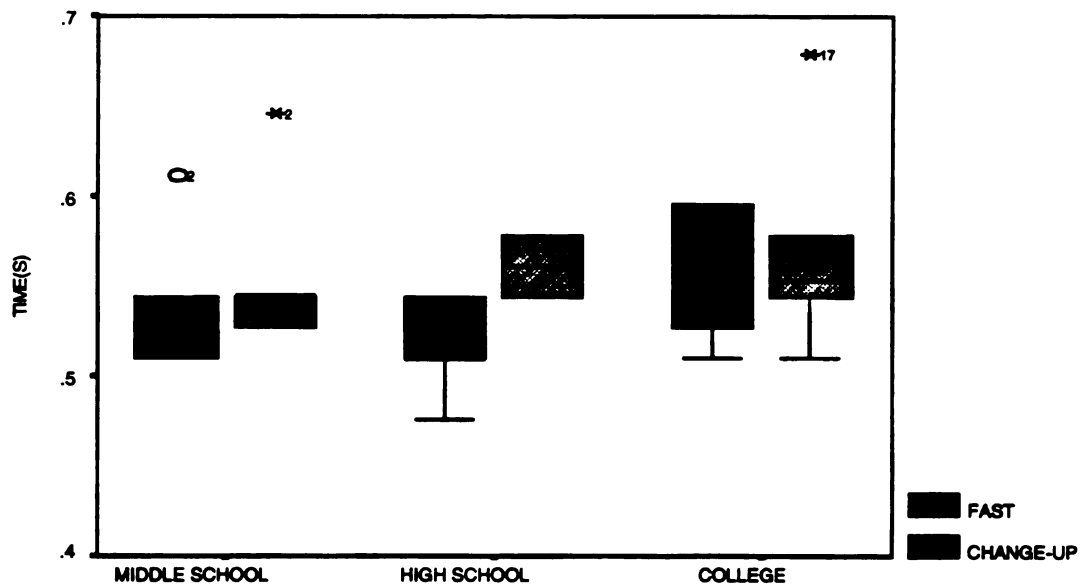


Figure 4.1a. Time interval A (stride foot takeoff from force platform to ball release).

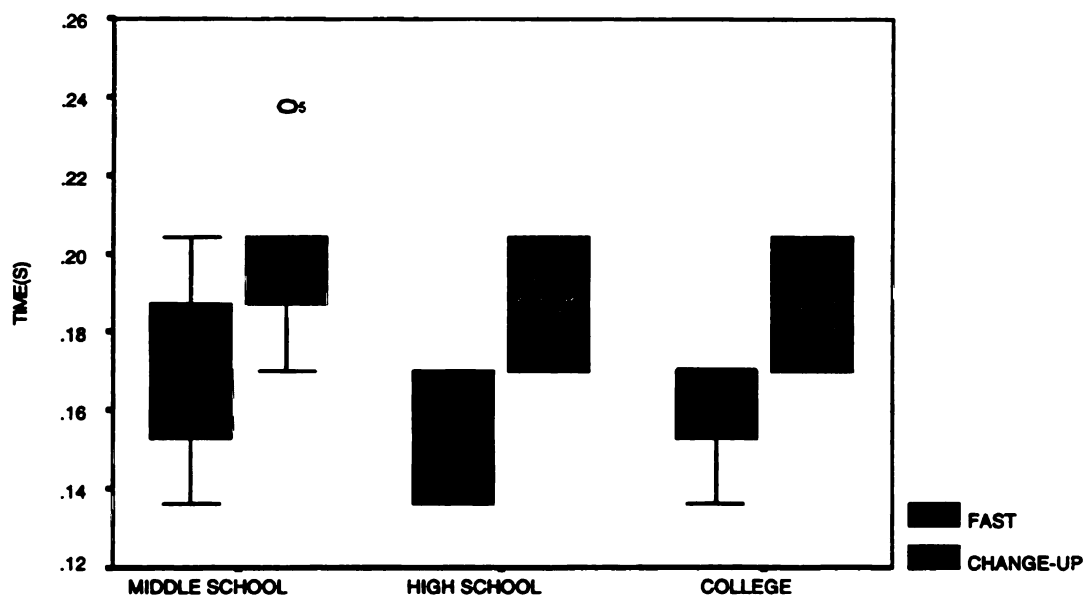


Figure 4.1b. Time interval B (highest point of pitching arm to ball release).

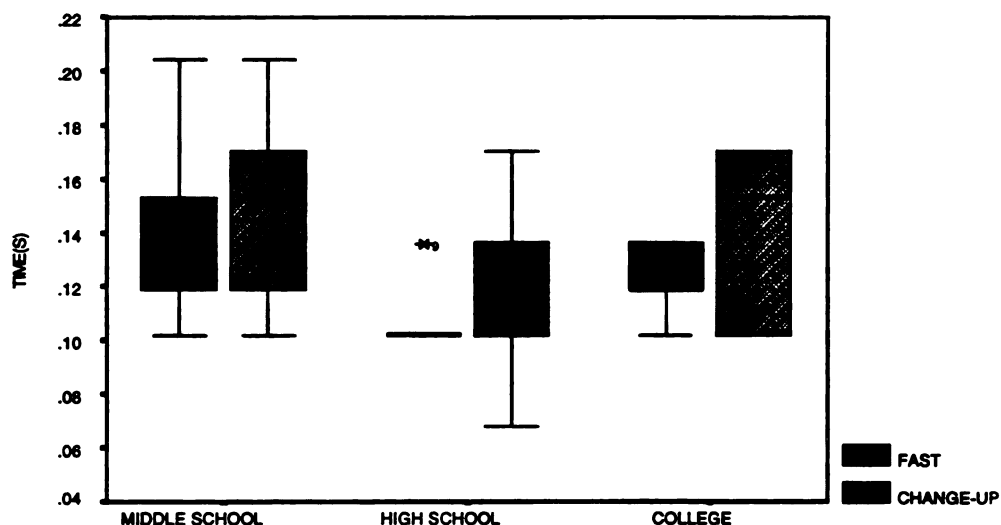


Figure 4.1b. Time interval C (stride foot contact with wooden frame to ball release).

for interval A, 0.155 s and 0.184 s for interval B, and 0.112 s and 0.126 s for interval C, respectively. The mean times for the fast and change-up pitches for the college subjects were 0.555 s and 0.570 s for interval A, 0.162 s and 0.184 s for interval B, and 0.122 s and 0.142 s for interval C, respectively.

Figure 4.1a-b shows the mean times for intervals A, B, and C for the fast pitches were significantly less than those for the change-up pitches ($P < .01$) (see Appendix B2). Statistically there was no significant difference in terms

of interval A, B, and C among the three groups. Still, using the mean value of the groups, some differences can be discerned. The mean times for intervals B and C for the fast and change-up pitches for the high school and college subjects were less than those for the middle school subjects. From Appendix B2, it is evident that the mean value of interval B was greater than that of interval C. This means that, on average, the pitching arm reached its highest point just before the stride foot contacted the wooden frame. This was true in all cases except for fast and change-up pitches of middle school subject 1 and college subject 4.

Pitching Parameters

Ball Velocity

The ball velocities of the best fast and change-up pitch in each of the three subject groups was calculated and reported in Appendix B3. The means, standard deviations, and differences in pitch velocity for each group are shown in Figure 4.2. The mean velocities of the fast and change-up pitches for the middle school subjects were 21.22 m/s and 18.34 m/s, with standard deviations equal to 2.56 m/s and 1.11 m/s, respectively. The mean velocities of the fast and change-up pitches for the high school subjects were 22.57 m/s and 17.03 m/s, with standard deviations equal to

2.39 m/s and 1.63 m/s, respectively. For the college subjects, the mean velocities were 23.39 m/s and 18.46 m/s, with standard deviations equal to 2.05 m/s and 1.54 m/s, respectively.

Among the three groups, statistically there was no significant difference in ball velocity (see Appendix B3). But when analyzing the mean data the average fast pitch velocity increased 1.13 m/s from the middle school to high school and 1.04 m/s from the high school to college. On the other hand, the average change-up pitch velocity did not show this type of trend from the middle school to the high school to college (see Figure 4.2).

When consolidating these results into differences in the average velocity between fast and change-up pitches there was a significant difference between the two styles of pitching ($P < .01$) (see Appendix B3). The average velocity difference for each of the three groups was 2.88 m/s, 5.55 m/s, and 4.93 m/s, respectively. The small difference value between the two types of pitches in the middle school subjects, compared to the velocity differences for the other two groups, may indicate that the middle school subjects were not sufficiently skilled to establish as large a difference between the velocity of their fast and change-up pitches.

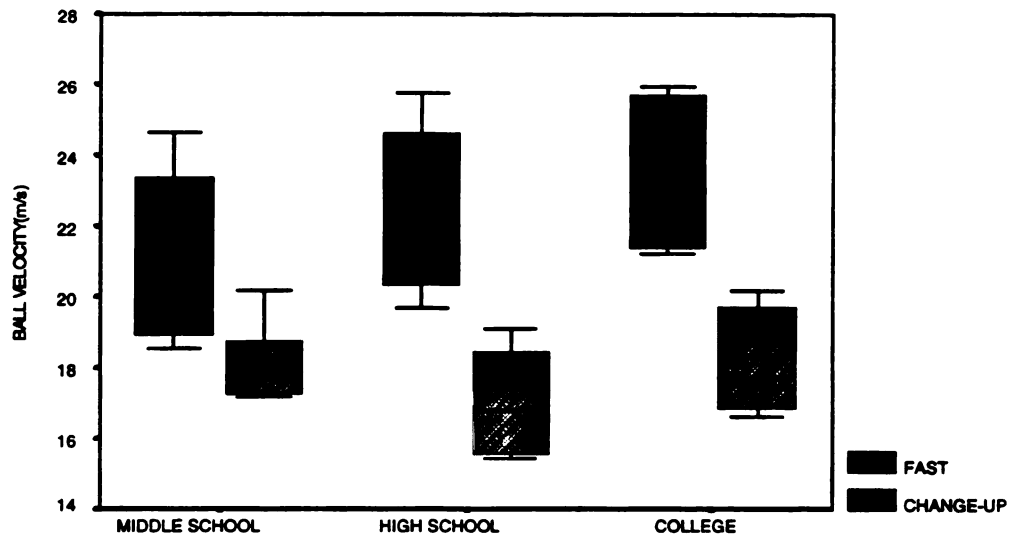


Figure 4.2. Windmill pitch ball velocities.

Stride Length

The stride length for each good pitch of middle school, high school, and college subjects is reported in Appendix B4. The measurement of each subject's height permitted the normalization of stride length. For each subject, stride length is reported as a percent of height. The mean normalized stride lengths for the fast and change-up pitches for the middle school subjects were $83.3 \pm 5.6\%$ and $83.5 \pm 8.4\%$, respectively. The mean normalized stride lengths for the fast and change-up pitches in the high school subjects were $90.6 \pm 11.9\%$ and $89.2 \pm 11.9\%$, respectively. The mean

normalized stride lengths for the fast and change-up pitches in the college subjects were $95.3 \pm 20.2\%$ and $93.5 \pm 20.7\%$, respectively.

Statistically there was no significant difference in the normalized stride length among the three groups (see Appendix B4). But from Figure 4.3, it is evident that there was an increase in normalized stride length with increased age group for both the fast and change-up pitches. The mean normalized stride length for the fast pitch increased 7.3% from the middle school to high school and 4.7% from the high school to college. Also, the mean normalized stride length for change-up pitch increased 5.8% from the middle school to the high school and 4.2% from the high school to the college.

The mean normalized stride lengths for the fast and change-up pitches within each group were not significantly different (see Appendix B4). However, the values of the standard deviations for the normalized stride lengths for both the fast and change-up pitches in the high school and college subjects were rather large. The data indicate an increase in variability with an increase in age group for both the fast and change-up pitches as noted in these standard deviation values. It was observed, from the video

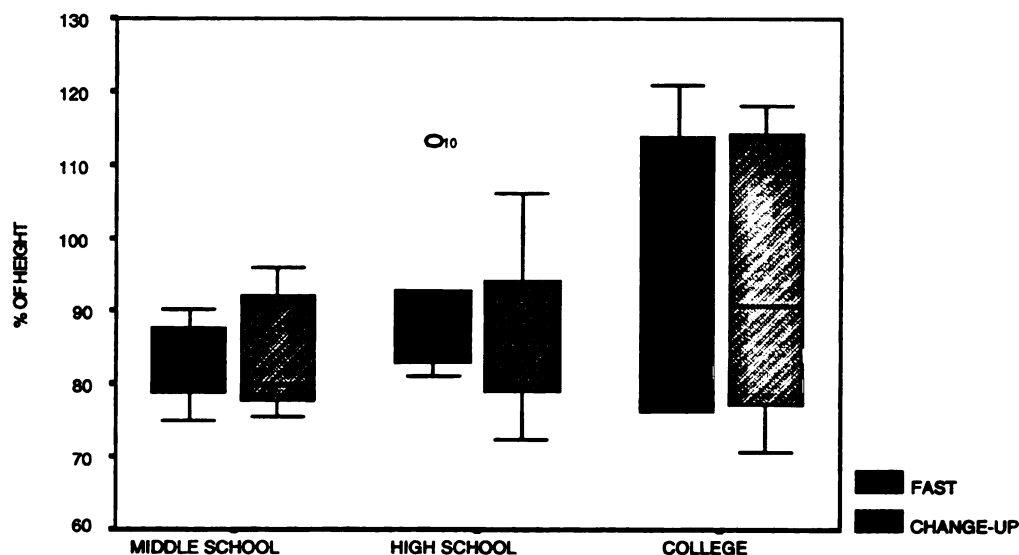


Figure 4.3. Normalized stride lengths.

tape records, that greater stride lengths were associated with subjects who tended to engage in a leaping motion (often referred to by softball participants as jumping). This leaping style increased in prevalence with increases in age group. For each subject, the rank of her normalized stride length within her subject group tended to be the same for both the fast and change-up pitches. Therefore, a dominant factor in normalized stride length appeared to be the style of delivery (step or leap).

Kinematics

Contributions to Ball Velocity

Factors that contribute to the velocity of the ball (BS) are the flexion of the shoulder (C1), elbow (C2), and wrist (C3); the rotation of the trunk (C4) and hip (C5); and the velocity of the c.m. of the whole body (C6). The contributions to the velocity of the ball by each of these factors for the three groups are shown in Figures 4.4. The vertical lines labeled TO, HP, and BR in Figures 4.4 designate the time of stride foot takeoff, highest position of the pitching arm, and point of the ball release, respectively. The patterns of the contribution made by each of the factors to the velocity of the ball during the pitching motion were in general similar among the three groups for the fast and change-up pitches as shown in Figures 4.4. The ball velocity usually decreased just before the takeoff on the stride foot, and then increased. Often, there was evidence of a decrease in ball velocity near the time of the highest point of the pitching arm. This was followed by a sharp increase in ball velocity until release. Figure 4.4 also shows that the contributions of various components to the velocity of the ball during the pitching motion were very similar in each of the three groups for both the fast and change-up pitches.

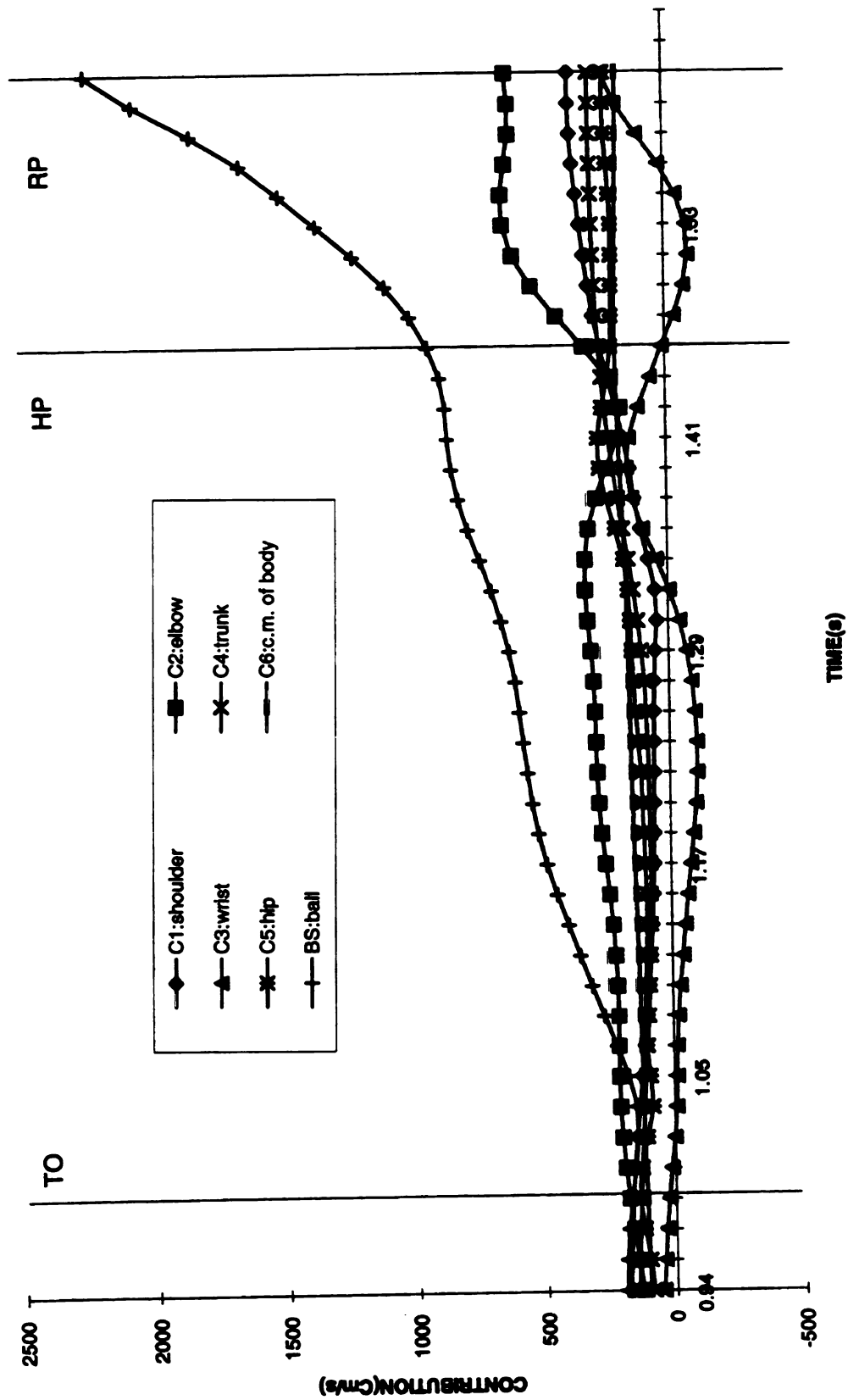


Figure 4.4a. Contribution to the ball velocity for the fast pitch for the middle school subject 2.

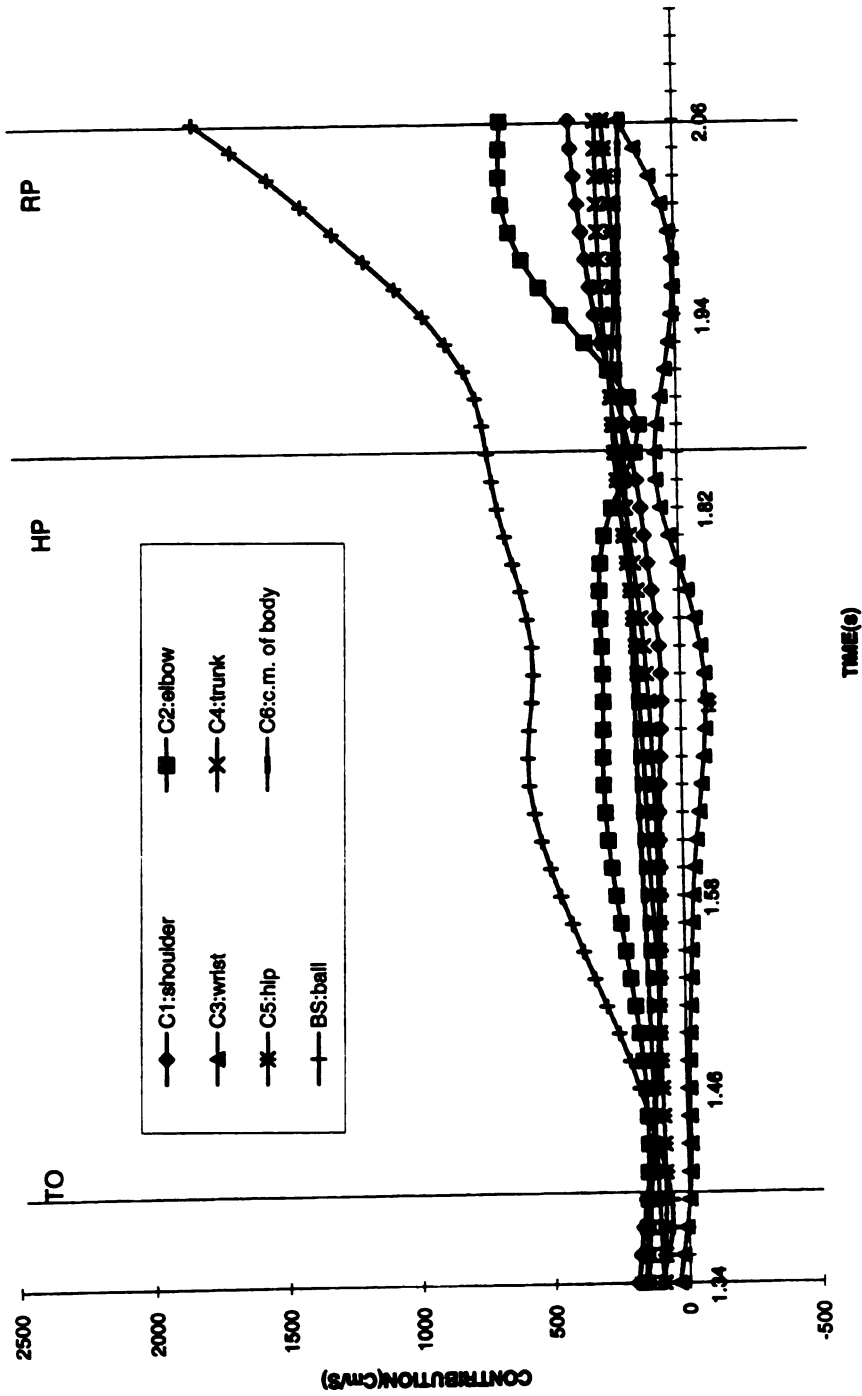


Figure 4.4b. Contribution to the ball velocity for the change-up pitch for the middle school subject 2.

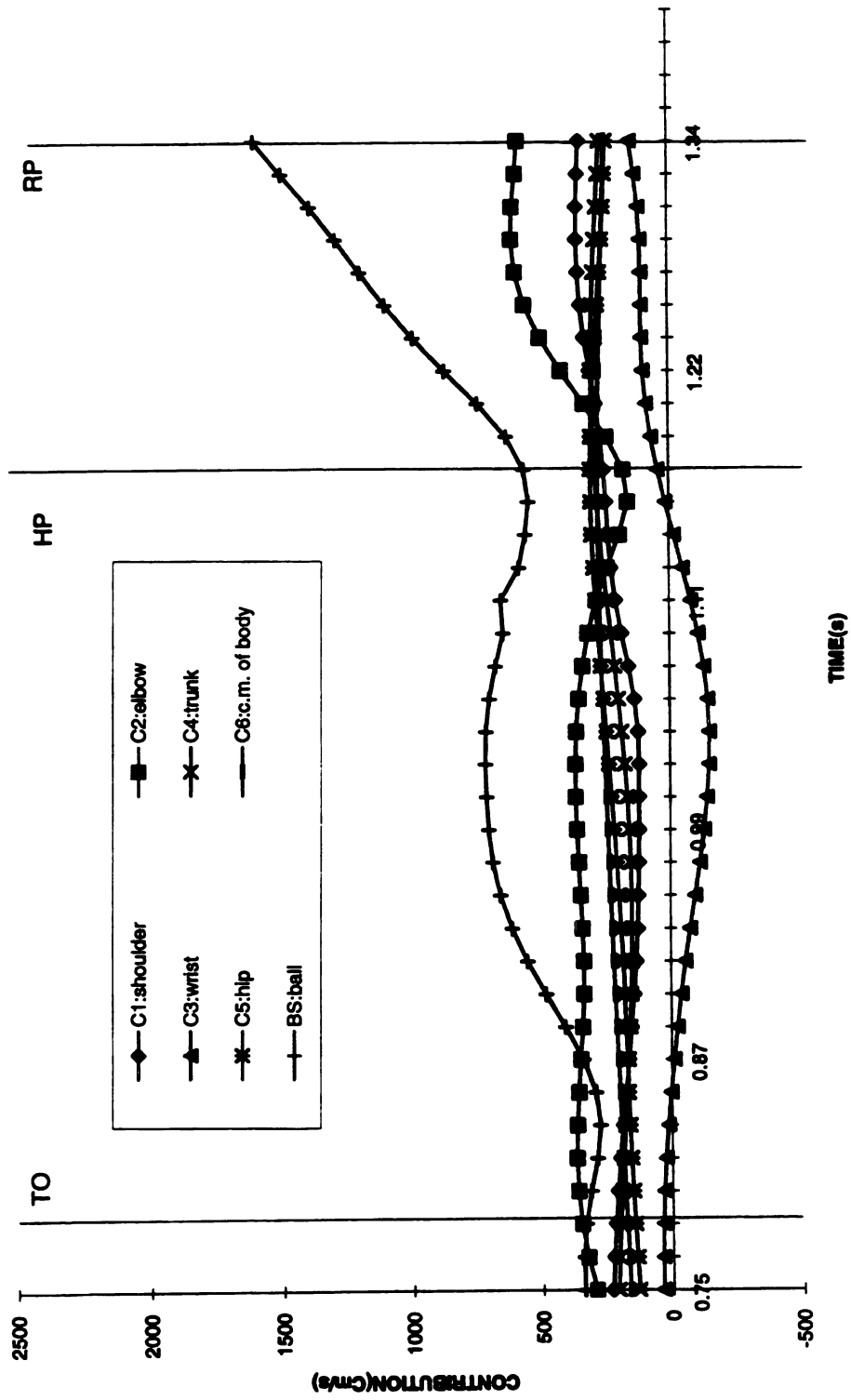


Figure 4.4c. Contribution to the ball velocity for the fast pitch for the high school subject 5.

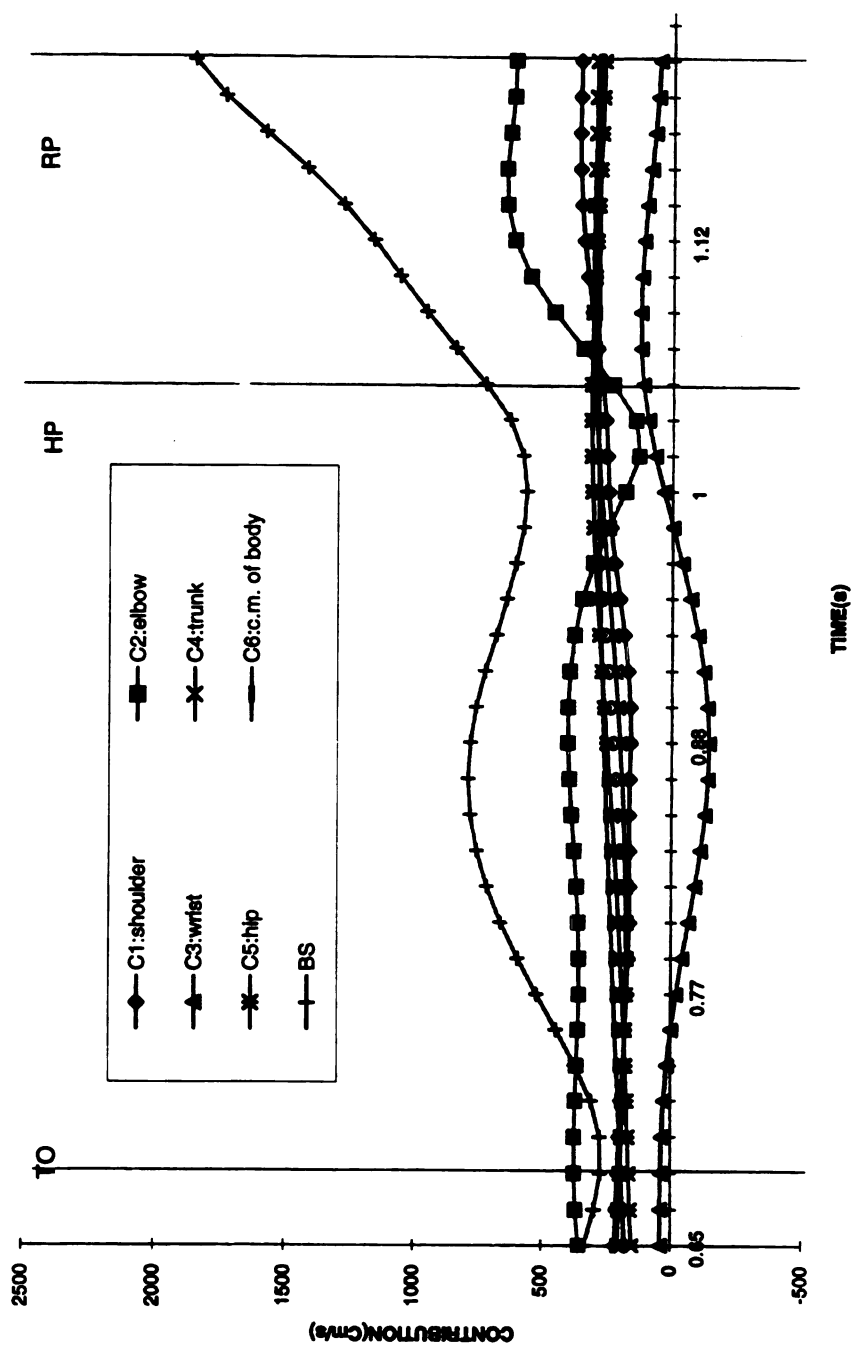


Figure 4.4d. Contribution to the ball velocity for the change-up pitch for the high school subject 5.

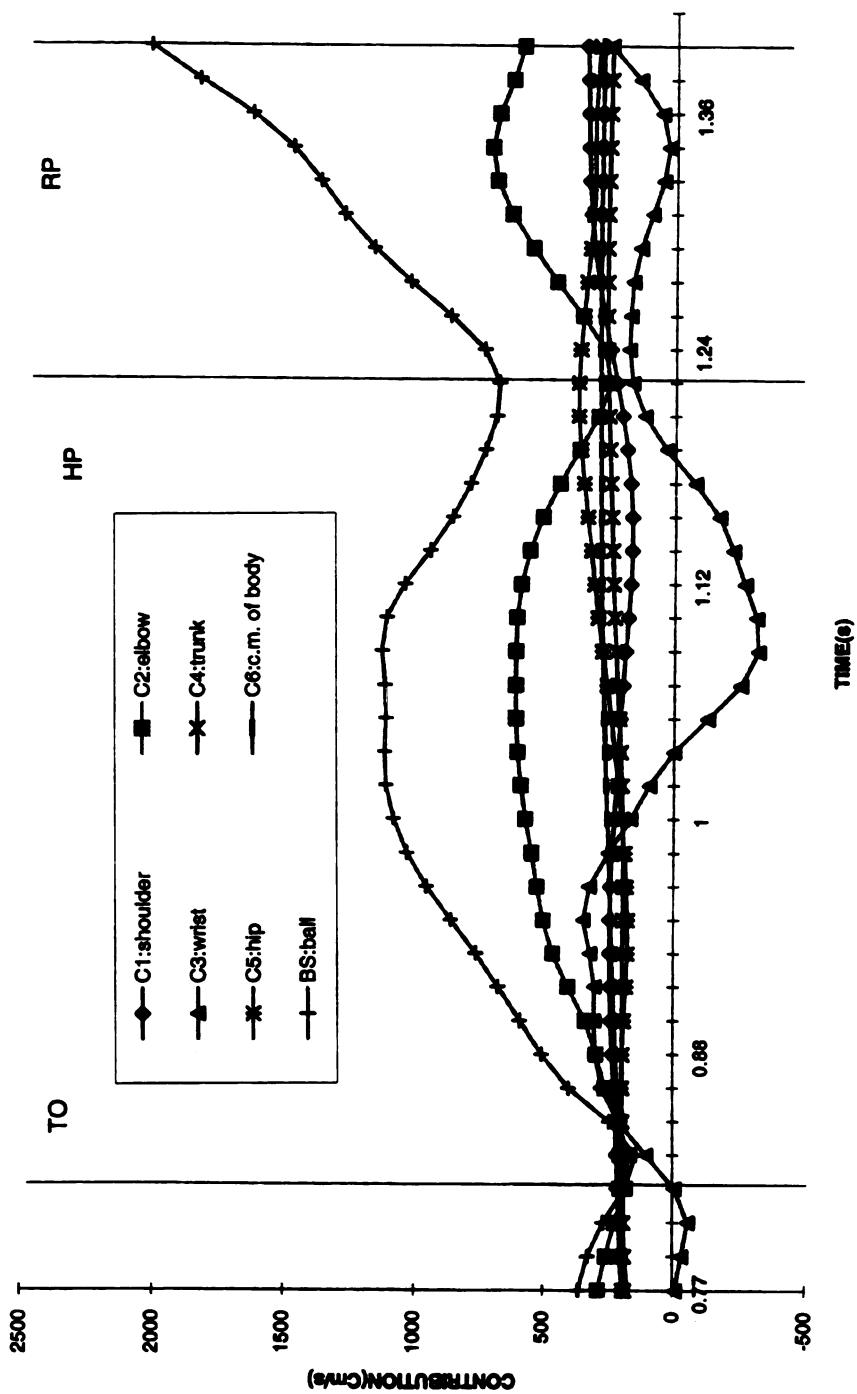


Figure 4.4e. Contribution to the ball velocity for the fast pitch for the college subject 2.

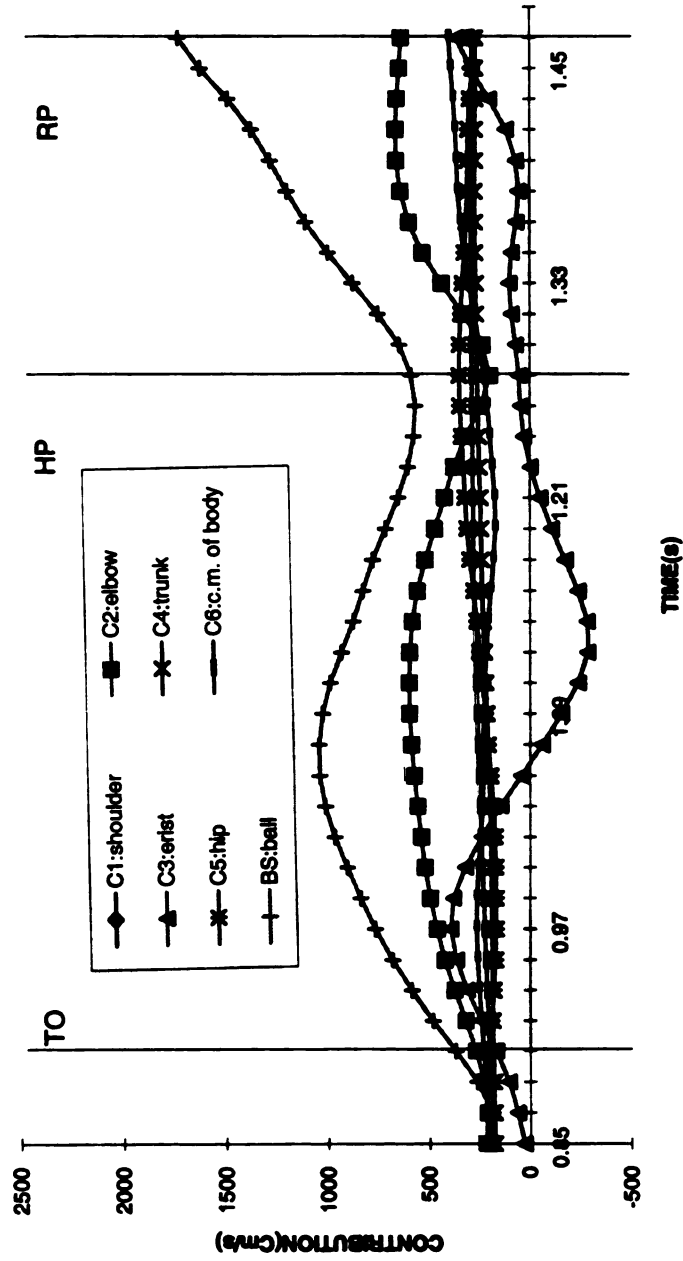


Figure 4.4f. Contribution to the ball velocity for the change-up pitch for the college subject 2.

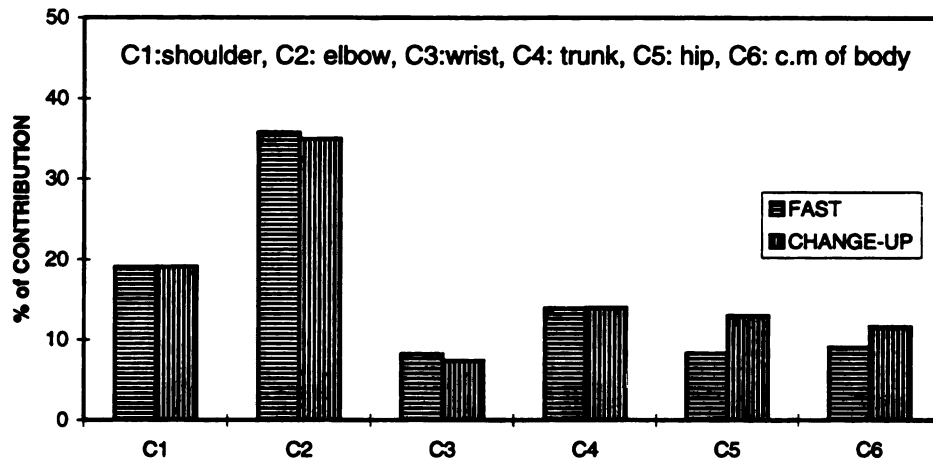


Figure 4.5a. The percentage of contribution to ball velocity at release in the middle school subjects.

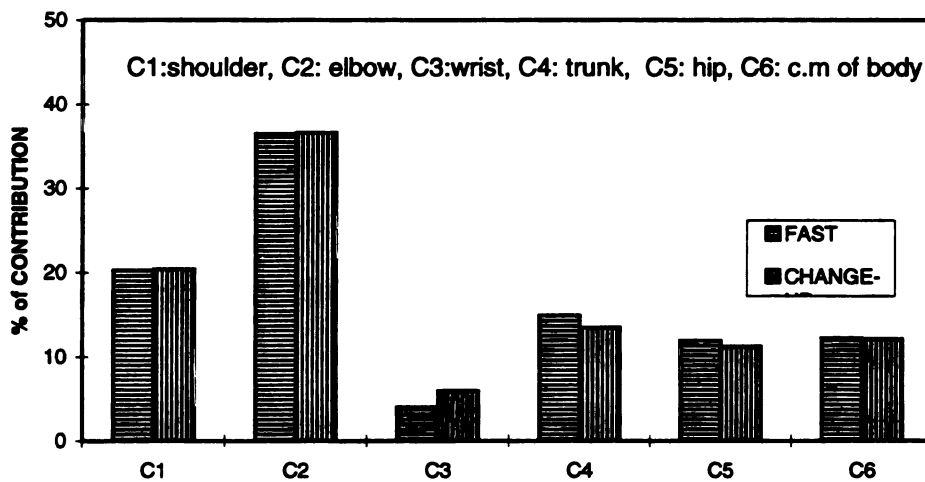


Figure 4.5b. The percentage of contribution to ball velocity at release in the high school subjects.

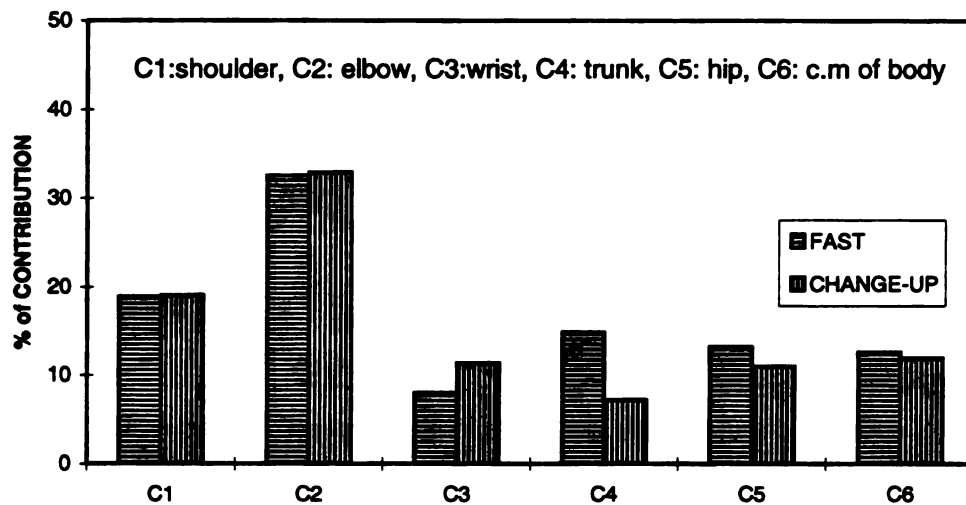


Figure 4.5c. The percentage of contribution to ball velocity at release in the college subjects.

The contributions of the various components to the ball velocity for each good pitch of the middle school, high school, and college subjects are reported in Appendix B5. Among each of the three groups for the fast and change-up pitches, the average values of contributions of each factor at the instant of ball release are were not significantly different. The average percentage contribution to ball velocity by the flexion of the shoulder (C1) and elbow (C2) and the rotation of the trunk (C4) and hip (C5) was 19.0%, 35.8%, 13.9%, and 8.3% for the fast pitch and 19.1%, 35.0%, 14.0%, and 12.9% for change-up pitch

for the middle school subjects; 20.3%, 36.5%, 15.0%, and 12.0% for the fast pitch and 20.4%, 36.7%, 13.5%, and 11.3% for change-up pitch for the high school subjects; and 18.9%, 32.5%, 14.9%, and 13.2% for the fast pitch and 19.0%, 32.9%, 7.2%, and 11.0% for the change-up pitch for the college subjects, respectively. The data indicates that the flexion of the elbow and the flexion of the shoulder for fast and change-up pitches were the major contributors to the velocity of the ball.

From Figure 4.5, it is evident that the percentage of the contribution to ball velocity between the fast and change-up pitches for shoulder flexion (C1) and elbow flexion (C2) among the three groups were similar. The percentage of the contribution to ball velocity of the rotation of the trunk (C4) and hip (C5) in the fast pitch for the high school and college subjects was higher than in change-up pitch, but in the middle school the C4 was similar and the C5 in the fast pitch was less than in the change-up pitch. It is evident in the section dealing with ball velocity that the velocity of the ball for the high school and college subjects was greater than for the middle school subjects. In view of this fact, the current data indicates that hip rotation contributed to the ball velocity.

Angular Displacement

The angular displacement of each of the pitching arm segments, plotted against time, for selected individuals in the three subject groups, for the fast and change-up pitches are shown in Figures 4.6. Three shoulder angles determine the position of the pitching arm: (flexion-extension in the X-Y plane (JD3) , horizontal abduction-adduction in the X-Z plane (JD2), and abduction-adduction in the Y-Z plane (JD1)).

Generally, during the pitching motion, the patterns of JD3, JD2 and JD1 were very similar in each group of subjects for the fast and the change-up pitches. JD3 gradually increased from takeoff of the stride foot (TO) to ball release (BR). JD2 decreased before the highest point of shoulder (HP), stayed more or less constant throughout the later part of the execution phase. JD1 decreased slightly and remained constant during the execution phase.

Figure 4.6 shows three representative subjects from each group; the pattern of JD3 was almost the same for the fast and change-up pitches in the same subject. Similarly, the patterns of JD2 were similar for the fast and change-up pitches in the same subject. The pattern of JD2 decreased well before the highest point of the shoulder for most subjects. The patterns of JD1 were very similar in the

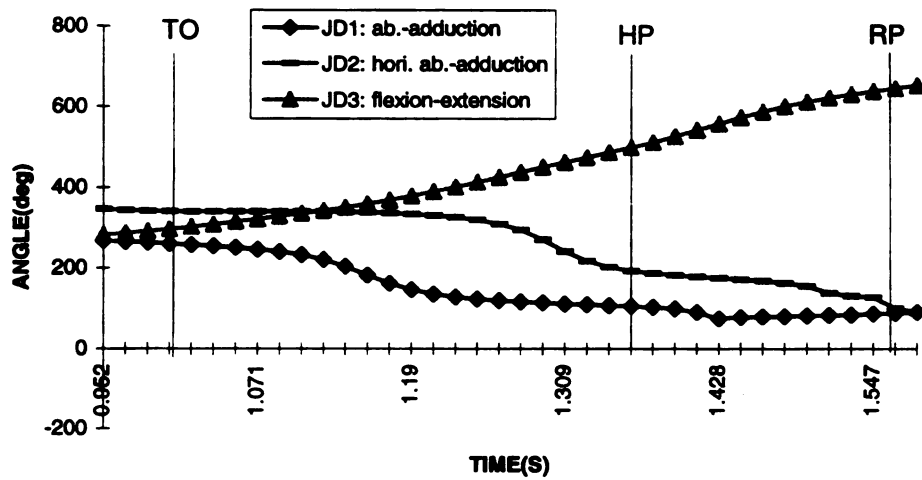


Figure 4.6a. Angular displacements of the arm for the fast pitch for the middle school subject 4.

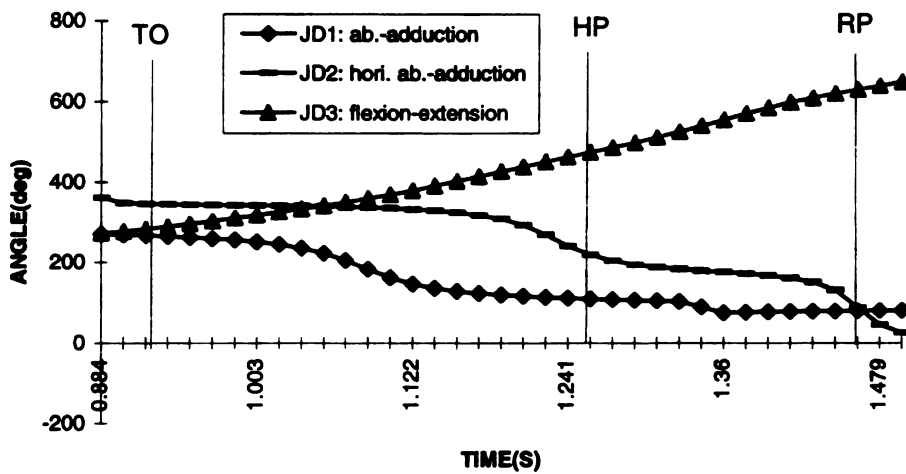


Figure 4.6b. Angular displacements of the arm for the change-up pitch for the middle school subject 4.

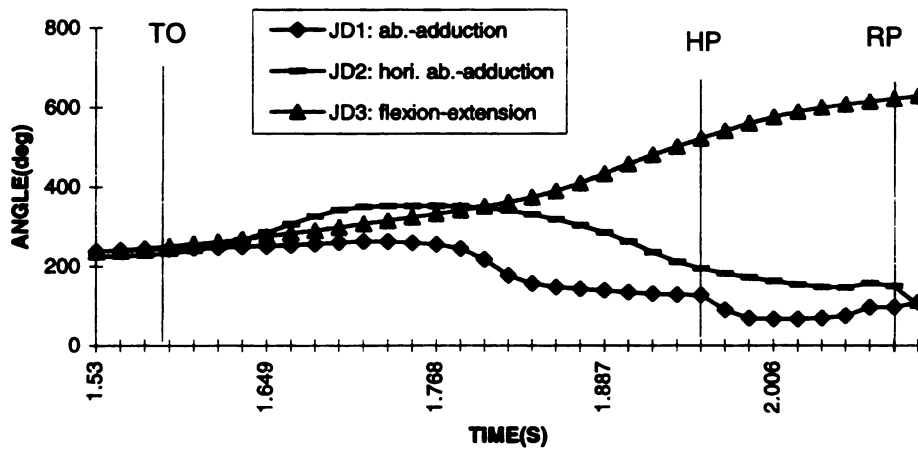


Figure 4.6c. Angular displacements of the arm for the fast pitch for the high school subject 5.

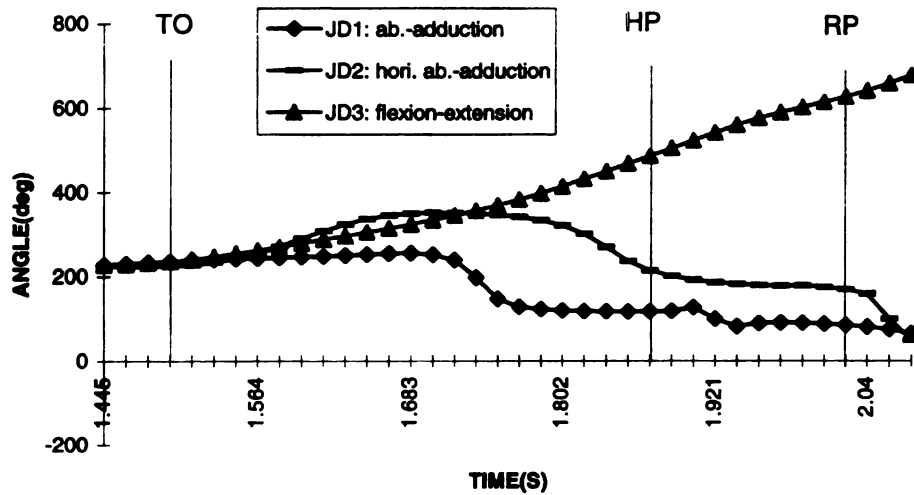


Figure 4.6d. Angular displacements of the arm for the change-up pitch for the high school subject 5.

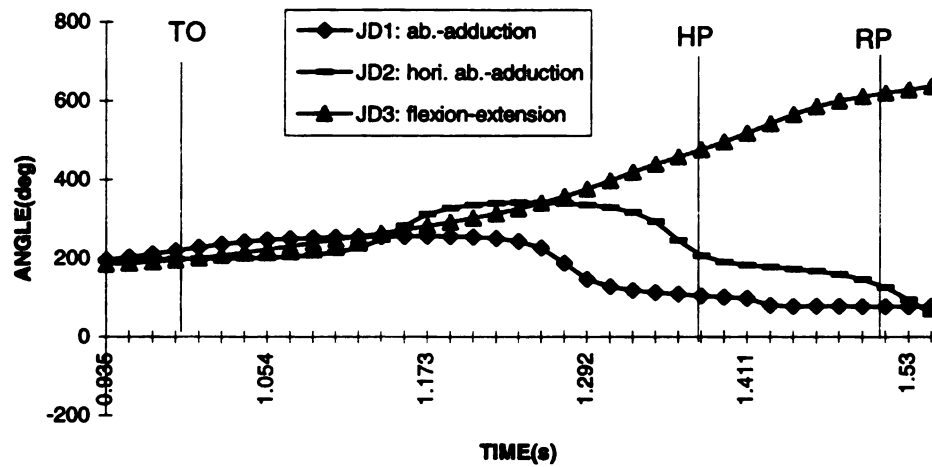


Figure 4.6e. Angular displacements of the arm for the fast pitch for the college subject 4.

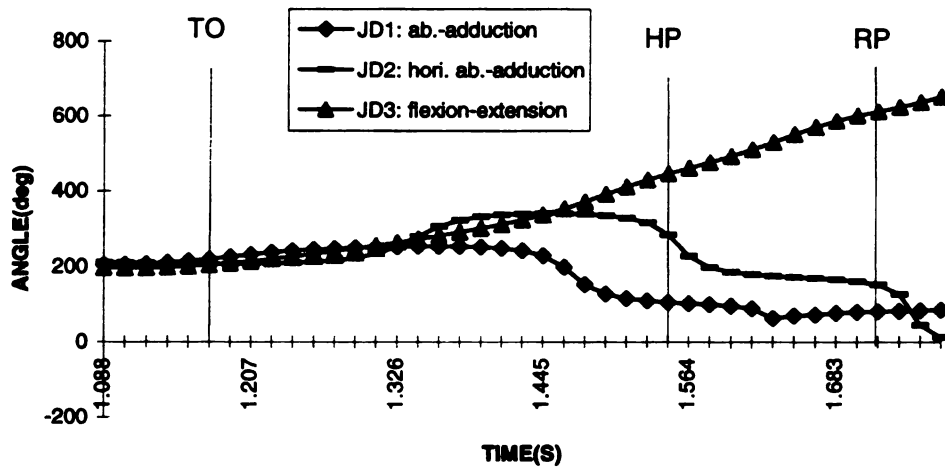


Figure 4.6f. Angular displacements of the arm for the change-up pitch for college subject 4.

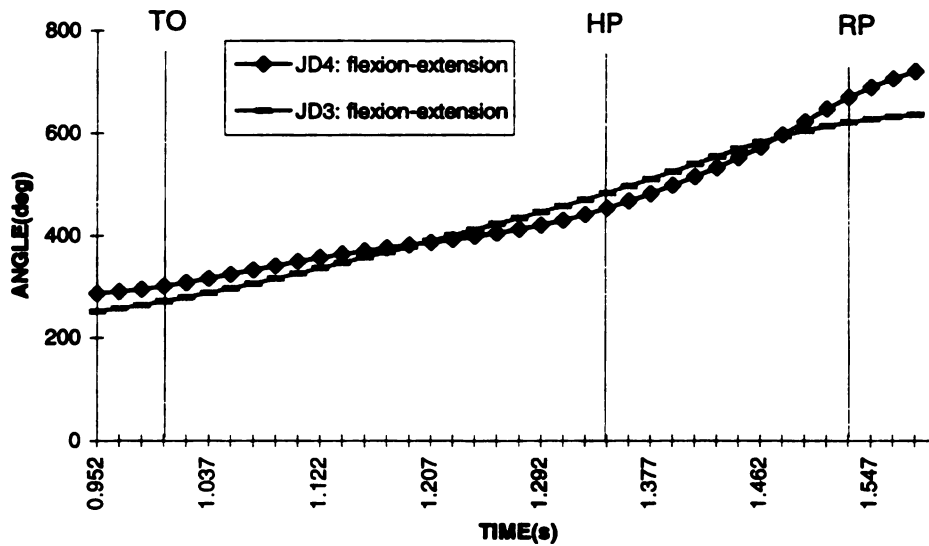


Figure 4.7a. Flexion-extension displacement of the forearm (JD4) and arm (JD3) for the fast pitch for the middle school subject 4.

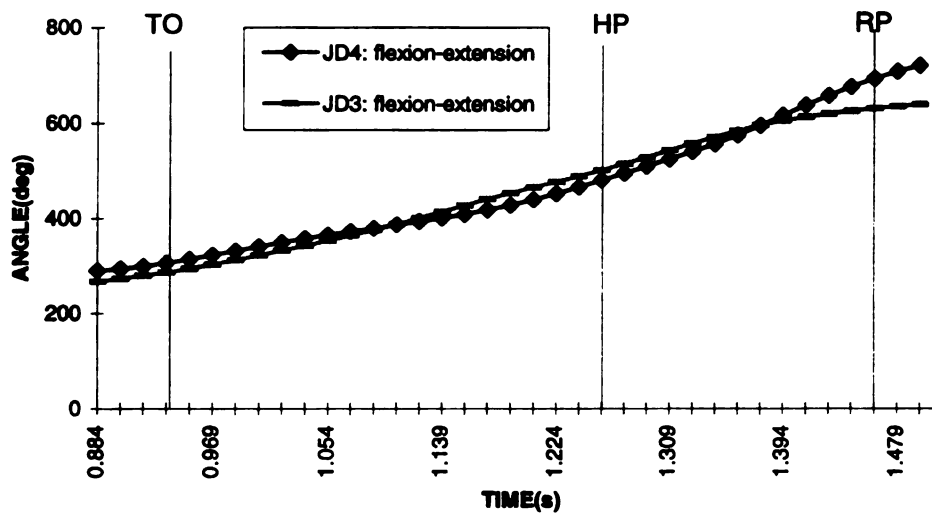


Figure 4.7b. Flexion-extension displacement of the forearm (JD4) and arm (JD3) for the change-up pitch for the middle school subject 4.

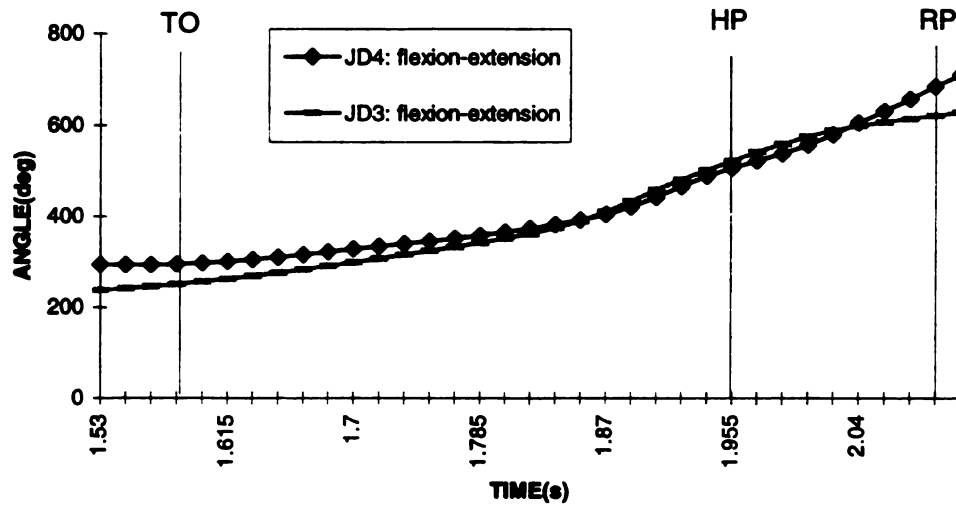


Figure 4.7c. Flexion-extension displacement of the forearm (JD4) and arm (JD3) for the fast pitch in the high school subject 5.

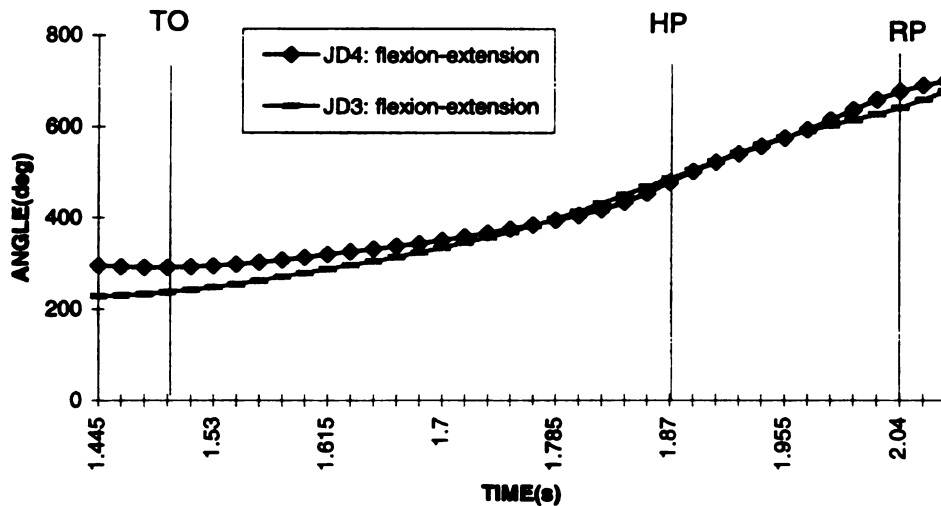


Figure 4.7d. Flexion-extension displacement of the forearm (JD4) and arm (JD3) for the change-up pitch for the high school subject 5.

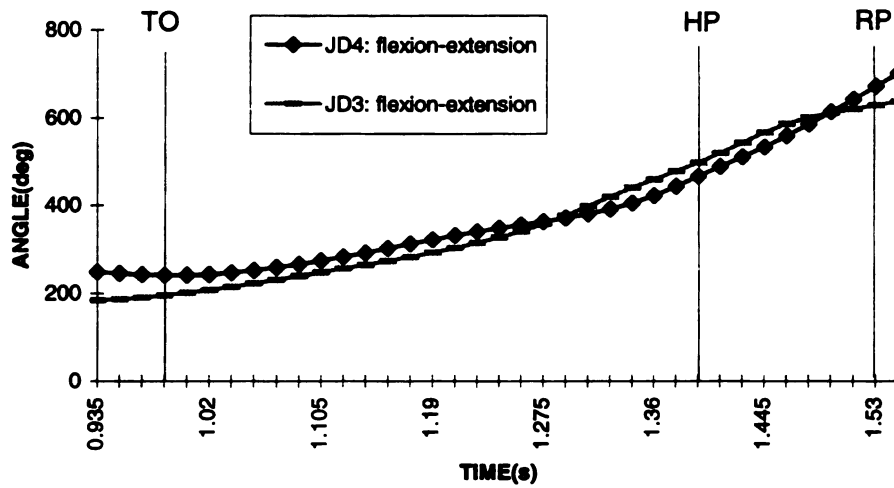


Figure 4.7e. Flexion-extension displacement of the forearm (JD4) and arm (JD3) for the fast pitch for the college subject 4.

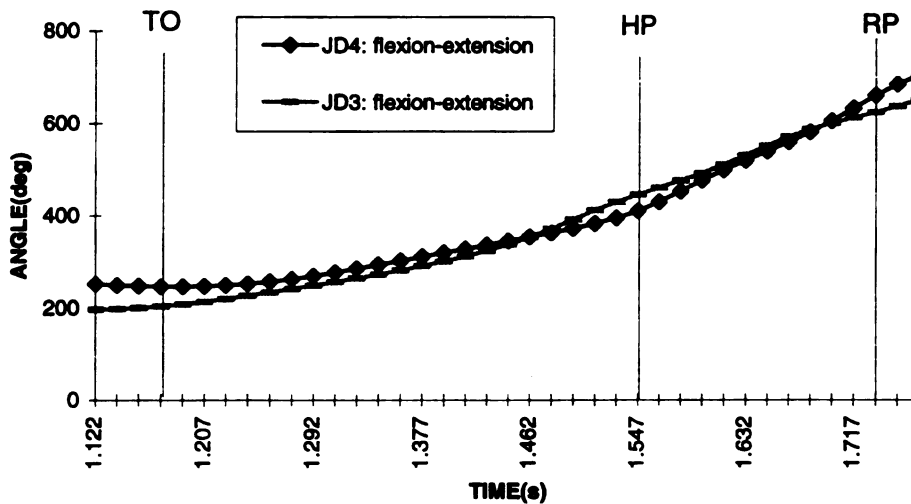


Figure 4.7f. Flexion-extension displacement of the forearm (JD4) and arm (JD3) for the change-up pitch for the college subject 4.

same subject for the fast and change-up pitches; also, these were similar until the release of the ball among the three groups.

The patterns of the displacement angle of the forearm in the X-Y plane (JD4) at release shown in Figure 4.7a-f were similar among the subjects in each group for the fast and change-up pitches. Generally, the JD4 increased from takeoff of the stride foot (T0) until the ball was released (BR). The two curves for JD3 and JD4 during the execution phase lie in close proximity until the point of the release of the ball. At this point, the curves for the forearm were turned upwards, and, in fact, the angles of the forearm bisected that of the arm. It is notable that the maximum slope of the displacement curve for the arm motion was reached earlier than that for the forearm, indicating that there was a sequential nature to the angular velocity of these segments in this movement.

The data presented in Appendix B6 permits a detailed description of angular displacement of the pitching arm of each subject during the pitching motion. From these data the rotation angle of arm at release point for the fast and change-up pitches among the three groups was calculated. At the instant of ball release, the average flexion of the arm (JD3) for the fast and change-up pitches was $625.2 \pm$

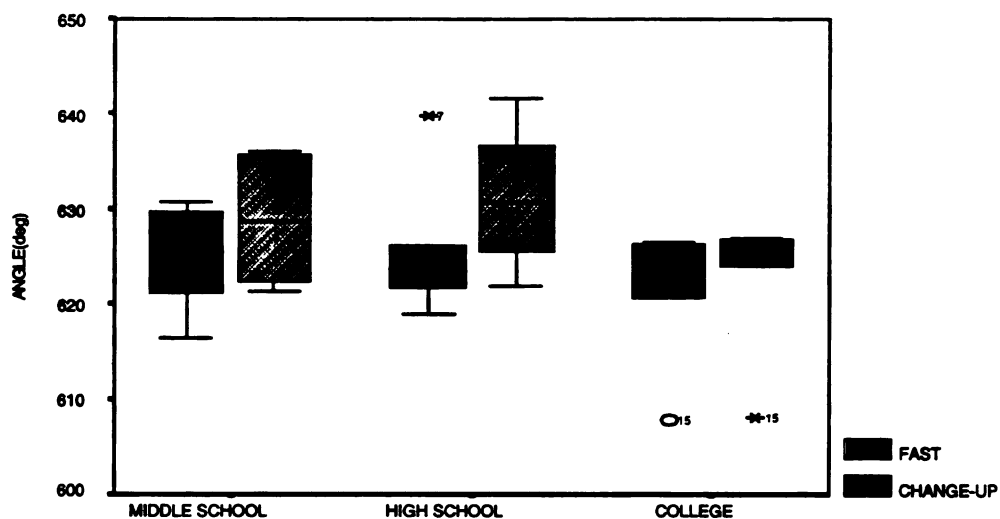


Figure 4.8 Flexion angle of the arm (JD3) at release.

5.4° and $628.8 \pm 6.3^\circ$ for the middle school subjects, $625.7 \pm 7.4^\circ$ and $631.1 \pm 7.4^\circ$ for the high school subjects, and $621.4 \pm 7.9^\circ$ and $622.7 \pm 7.2^\circ$ for the college subjects, respectively. This result shows that the arm was more flexed for the change-up pitch than for the fast pitch.

Statistically JD3 among the three groups was not significantly different (see Appendix B6). But from Figure 4.8 it is evident that the mean of JD3 for the fast pitch among the three groups at release was less than that for the change up pitch. The mean of JD3 in the fast and change-up

pitches for the college was less than that of the other groups.

The average flexion-extension angles at the elbow joint during the pitching motion at release are reported in Appendix B7. Statistical result indicates that JD4 was significantly different between two styles of pitches ($P < .05$) (see Appendix B7). The average flexion-extension angles at release point for the fast and change-up pitches were $140.33 \pm 12.30^\circ$ and $145.82 \pm 9.42^\circ$ for the middle school subjects, $146.27 \pm 16.64^\circ$ and $156.51 \pm 6.23^\circ$ for the high school subjects, and $142.93 \pm 5.30^\circ$ and $148.35 \pm 9.51^\circ$ for the college subjects, respectively. As in the case of the arm, these results indicate that the elbow were more flexed for the change-up pitch than for the fast pitch. However, no consistent pattern among the three groups was evident.

Angular Velocity

The angular velocities at the shoulder for the arm segment of the three representative subjects for the fast and change-up pitches are shown in Figures 4.9a-f. The three angular velocities at the shoulder joint are flexion-extension in the X-Y plane (JA3), abduction-adduction in the Y-Z plane (JA1), and horizontal abduction-adduction in the X-Z plane (JA2). The interpretation of segmental angular

velocities are as follows: the positive values for flexion-extension indicate that the arm is flexing, the negative values for abduction-adduction indicate that the arm is adducting, and the negative values for horizontal abduction-adduction indicate that the arm is horizontally abducting.

The patterns of JA1, JA2, and JA3 during the pitching motion were similar among each group for fast and change-up pitches. Generally, the pattern of JA3 was smooth, but the patterns of JA1 and JA2 were varied. The maximum of JA3 for the fast and change-up pitches was reached at approximately the highest point of the shoulder. From Figure 4.9 it is evident that during the execution phase the arm flexed, adducted, and horizontally abducted in the most of the subjects.

The patterns of the flexion-extension angular velocity at the elbow in the X-Y plane (JA4) during the execution phase shown in Figure 4.10 were roughly similar for the fast and change-up pitches among the three groups. During the execution phase, JA4 demonstrated flexion. The peak velocity of JA4 for the fast and change-up pitches was reached just before the release of the ball.

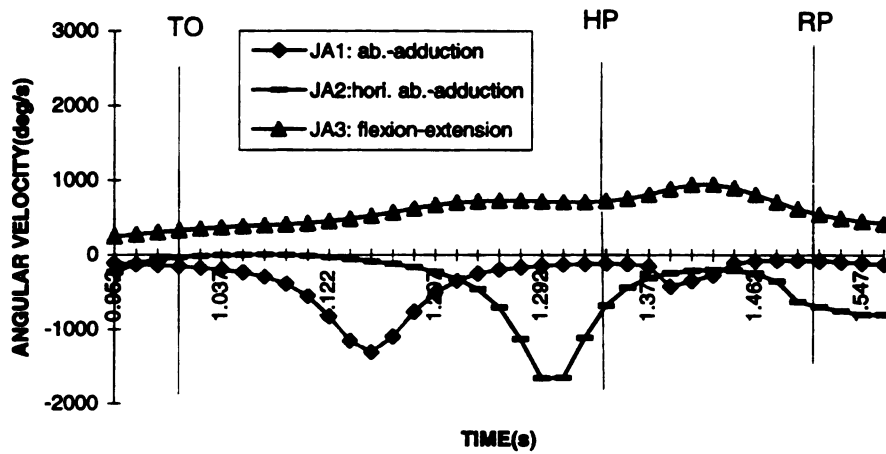


Figure 4.9a. Angular velocity at the shoulder for the fast pitch for the middle school subject 3.

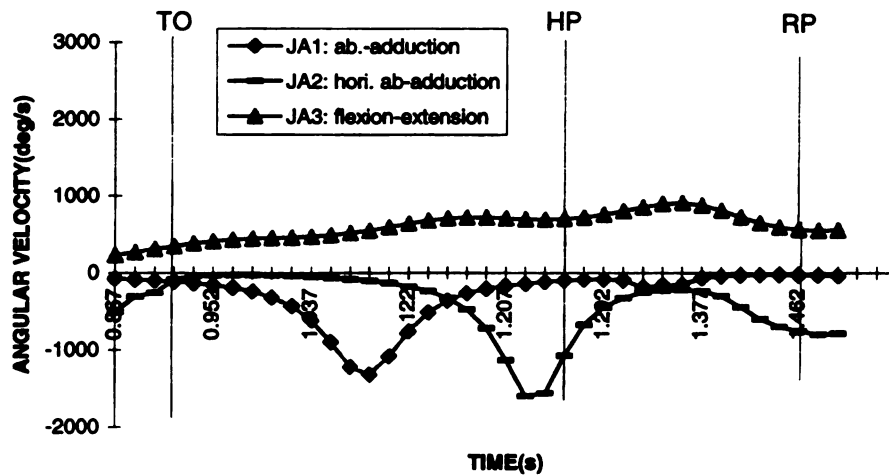


Figure 4.9b. Angular velocity at the shoulder for the change-up pitch for the middle school subject 3.

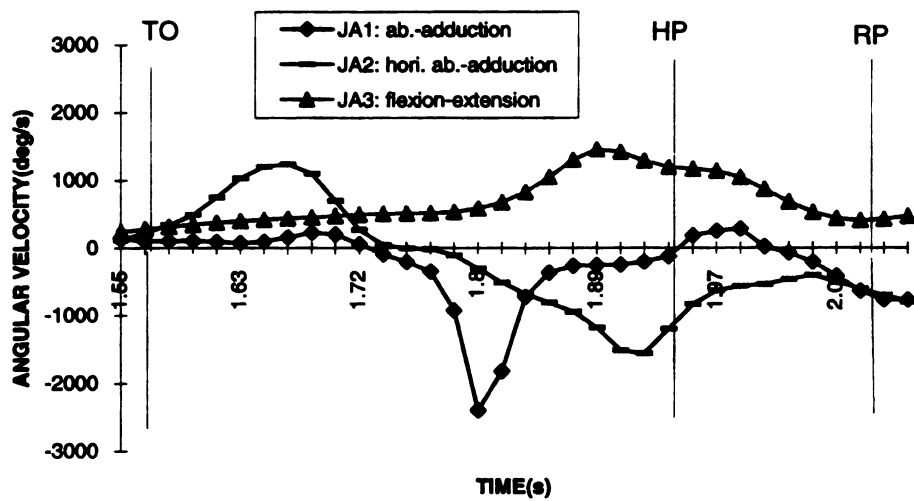


Figure 4.9c. Angular velocity at the shoulder for the fast pitch for the high school subject 3.

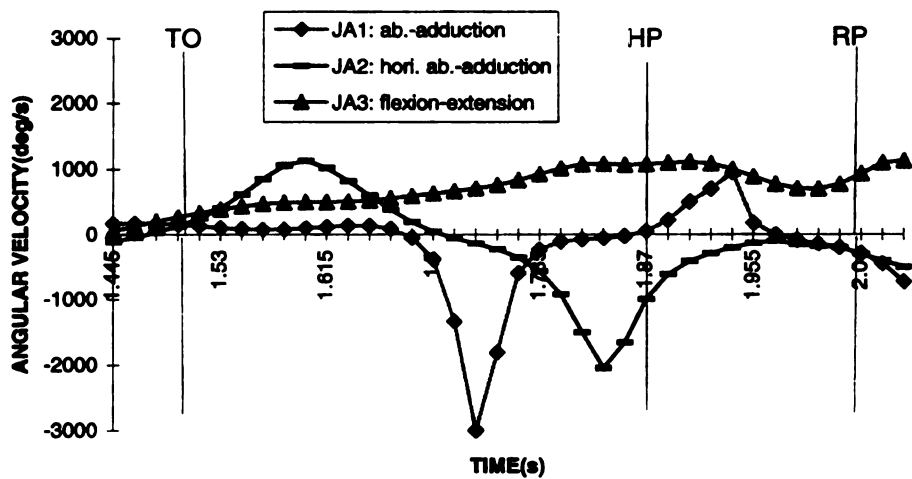


Figure 4.9d. Angular velocity at the shoulder for the change-up pitch for the high school subject 3.

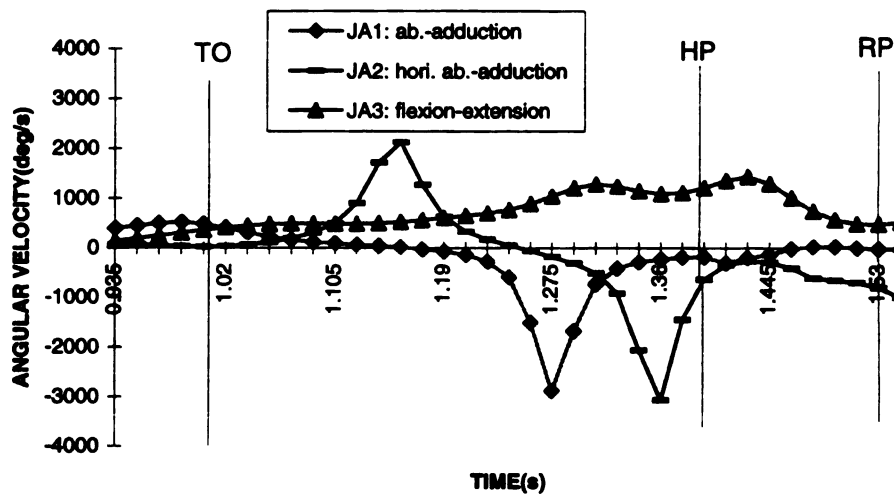


Figure 4.9e. Angular velocity at the shoulder for the fast pitch for the college subject 5.

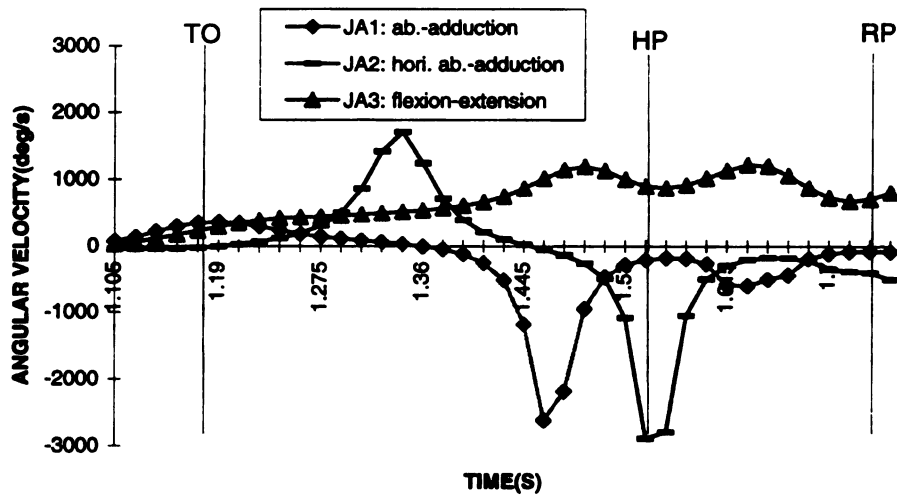


Figure 4.9f. Angular velocity at the shoulder for the change-up pitch in the college subject 5.

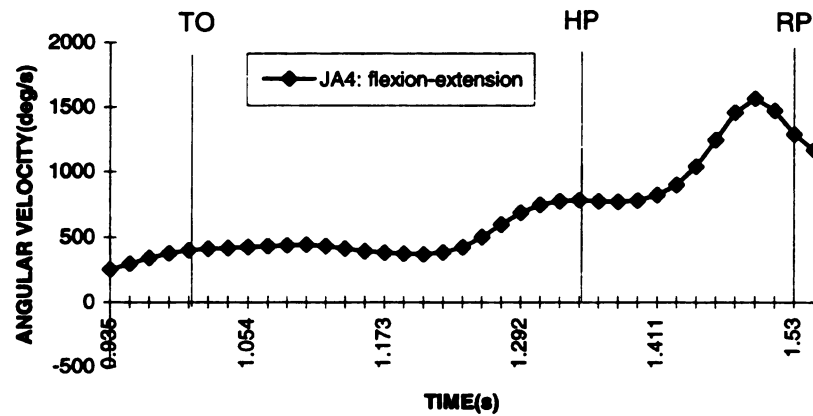


Figure 4.10a. Angular velocity at the elbow for the fast pitch for the middle school: subject 3.

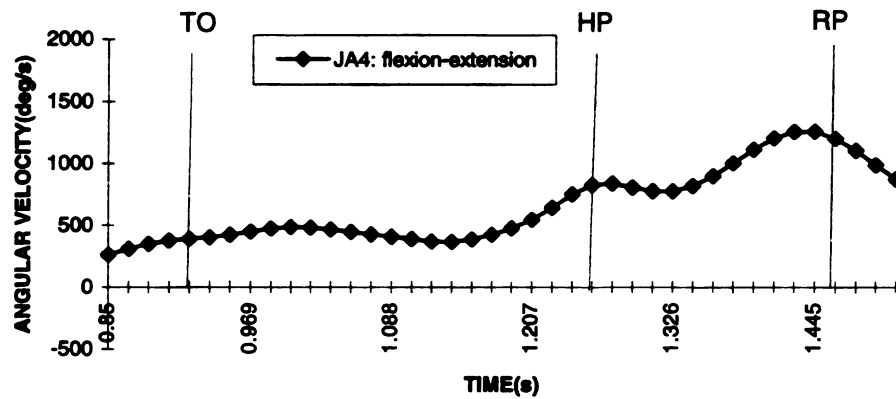


Figure 4.10b. Angular velocity at the elbow for the change-up pitch for the middle school subject 3.

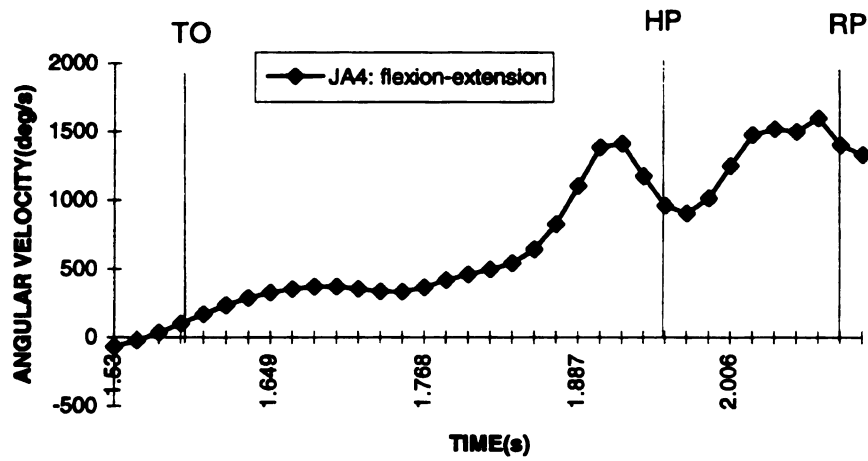


Figure 4.10c. Angular velocity at the elbow for the fast pitch for the high school subject 3.

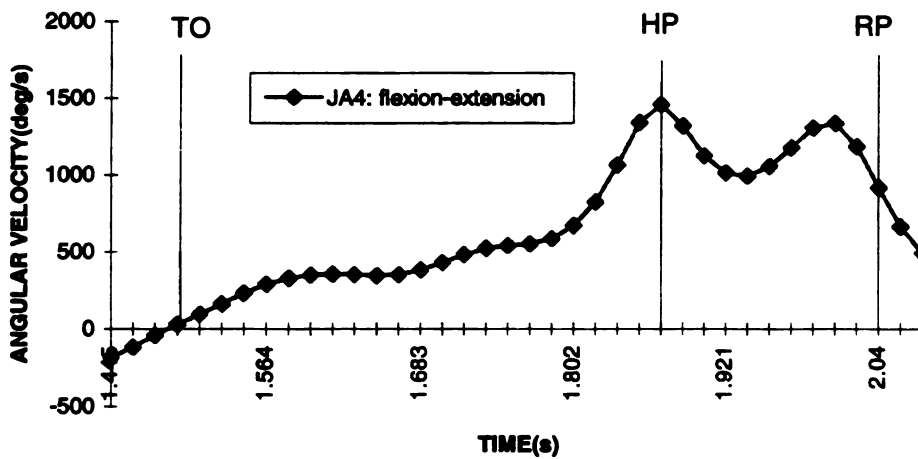


Figure 4.10d. Angular velocity at the elbow for the change-up pitch for the high school subject 3.

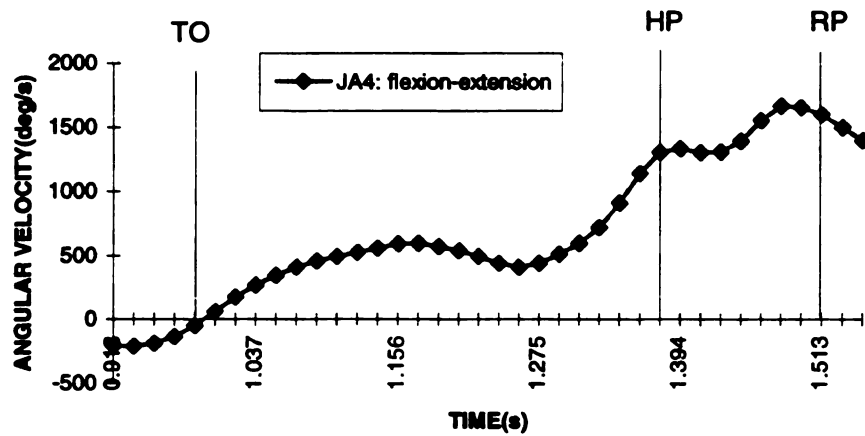


Figure 4.10e. Angular velocity at the elbow for the fast pitch for the college subject 5.

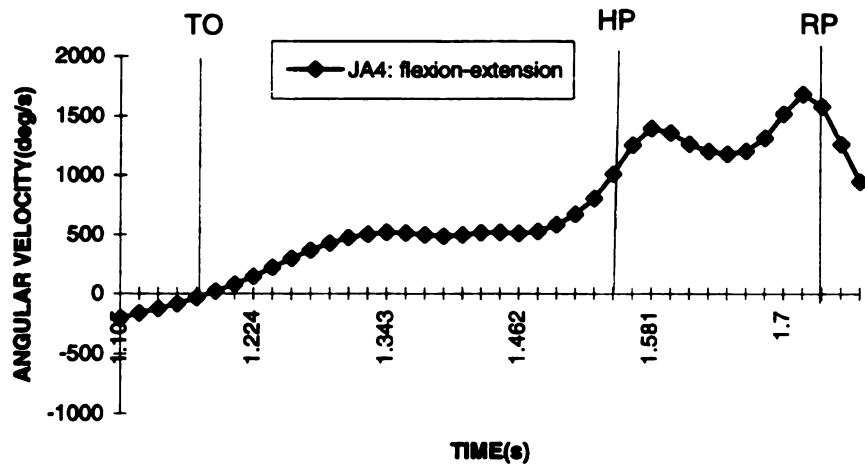


Figure 4.10f. Angular velocity at the elbow for the change-up pitch for the college subject 5.

The average peak angular velocity of JA3 at the shoulder among the three groups during the windmill pitching is reported in Appendix B8. The average peak angular velocity of flexion at the shoulder for the fast and change-up pitches was 1064.2 ± 154.7 deg/s and 999.4 ± 142.6 deg/s for the middle school subjects, 1369.7 ± 104.2 deg/s and 1120.2 ± 67.9 deg/s for the high school subjects, and 1152.6 ± 200.8 deg/s and 1075.3 ± 162.3 deg/s for the college subjects, respectively.

Statistical data indicates that there were significant differences in JA3 at the shoulder among the three groups and between two styles of pitches ($P < .01$) (see Appendix B8). From Figure 4.11, the mean peak angular velocity of the JA3 for the fast pitch among the three groups was higher than that for the change-up pitch. For the fast pitch the mean peak angular velocity of JA3 for the high school subjects was higher than that for the other groups. Also, in the change-up pitch, the mean peak angular velocity of JA3 for the high school subjects was the highest while that of the middle school subjects was the lowest.

The average peak angular velocity of extension-flexion at the elbow during the windmill pitching is reported in Appendix B8. The average peak angular velocity of

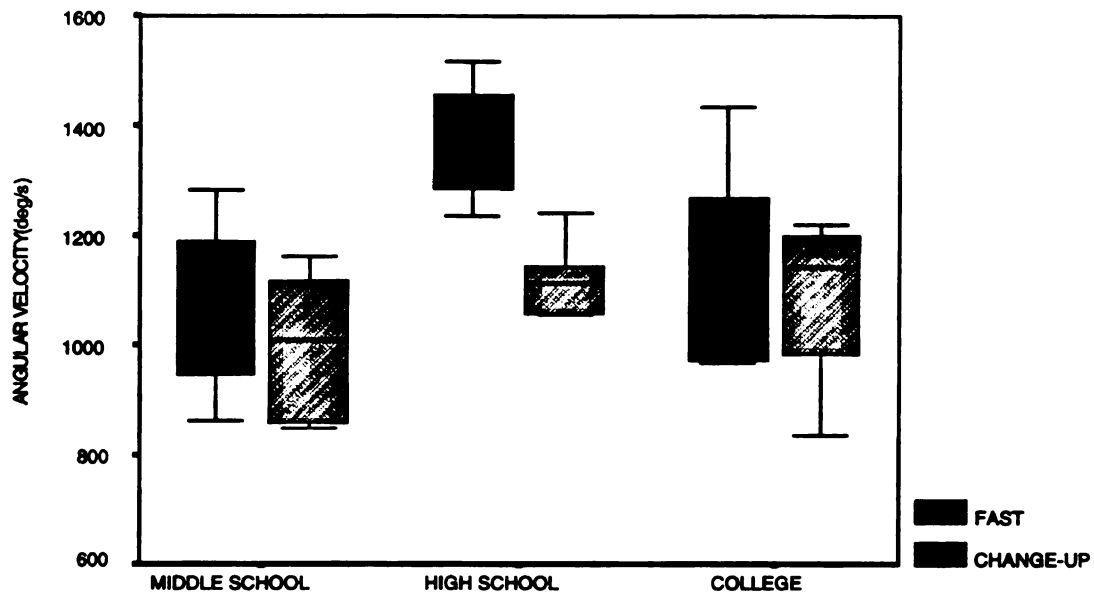


Figure 4.11 Peak flexion velocity of the shoulder joint (JA3) at ball release.

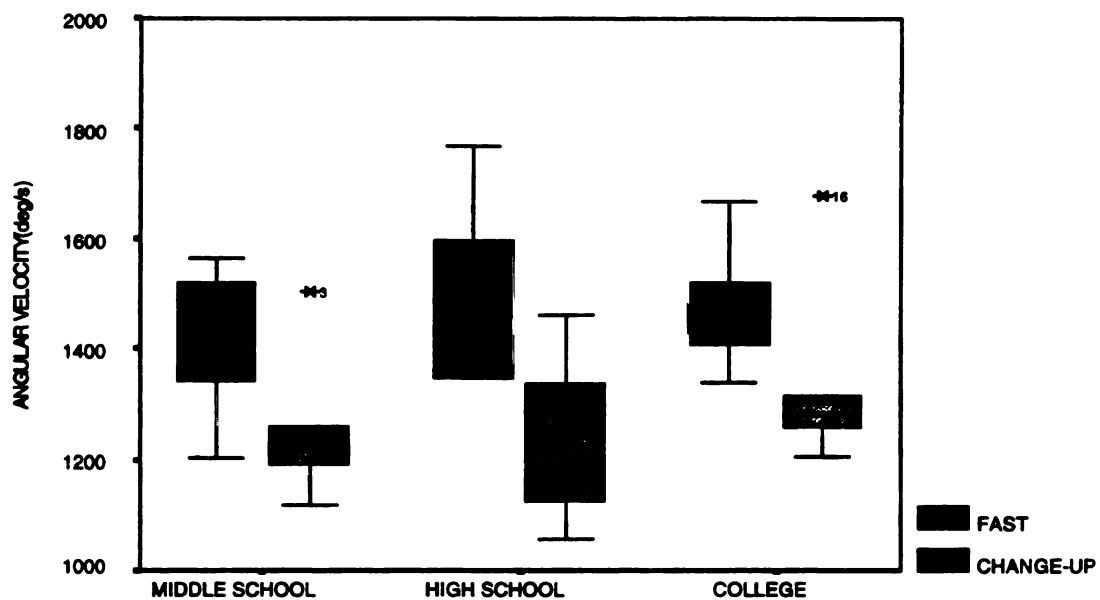


Figure 4.12 Peak flexion velocity of the elbow joint (JA4) at ball release.

flexion at the elbow for the fast and change-up pitches were 1492.5 ± 171.5 deg/s and 1238.0 ± 144.6 deg/s for the middle school subjects, 1430.6 ± 136.6 deg/s and 1262.7 ± 130.5 deg/s for the high school subjects, and 1479.5 ± 124.1 deg/s and 1347.9 ± 189.4 deg/s for the college subjects, respectively.

Statistical data indicates that there were significant differences in JA4 at the elbow between two styles of pitches ($P < .01$) but there was no significant difference among the three groups (see Appendix B8). Figure 4.12 gives the mean peak angular velocities of JA4 for the fast and change-up pitches for the three groups. It should be noted that mean peak angular velocity was higher for the fast pitch than for the change-up pitch. Statistically, there were no differences among the three groups, but from the mean data the mean peak angular velocity of JA4 for the college and high school subjects for the fast pitch was higher than that for the middle school subjects. Also, the mean peak angular velocity of JA4 for the middle school subjects for the change-up pitch was similar to the high school subjects and less than that for the college subjects.

Kinetics

The kinetic data is divided into three parts: (1) resultant joint forces, (2) resultant joint torques, and (3) ground reaction forces.

Resultant Joint Forces

The three components (X force (JF1), Y force (JF2), and Z force(JF3)) of the resultant joint forces at the shoulder, for three representative subjects (middle school subject 1, high school subject 5, and college subject 4) are shown in Figure 4.13. The patterns of JF1, JF2, and JF3 during the pitching motion for most subjects in the fast and change-up pitches among the three groups, were very similar. JF1 and JF2 demonstrated greater magnitudes than JF3.

The patterns of JF1 gradually increased from the highest point of shoulder (HP) until approximately the middle of the execution phase, then decreased until the point of the release of the ball. JF1 generally had a positive magnitude during the execution phase and reached a peak value around the middle of the this phase. The patterns of JF2 for most subjects were also similar. JF2 decreased until around the highest point of shoulder(HP) was achieved, then gradually increased throughout most of the execution phase, reaching peak just prior to the release of the ball. JF3 of the middle school subject 3, for the fast pitch, had

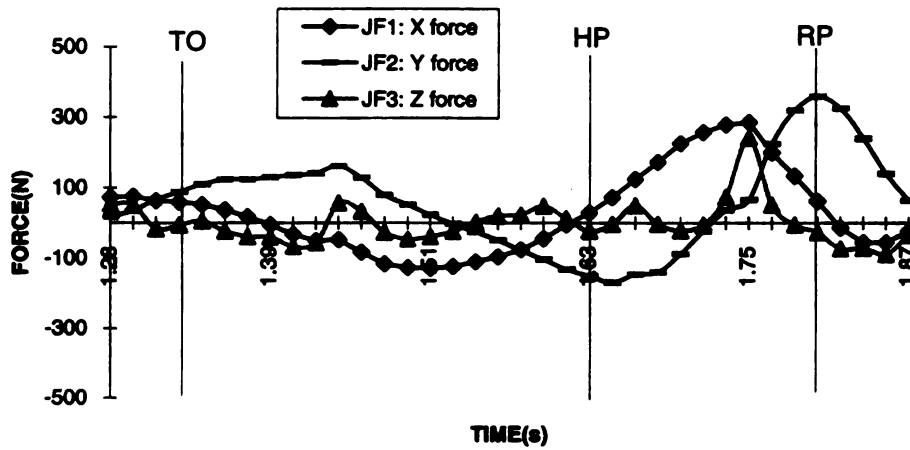


Figure 4.13a. Resultant joint force at the shoulder for the fast pitch for the middle school subject 1.

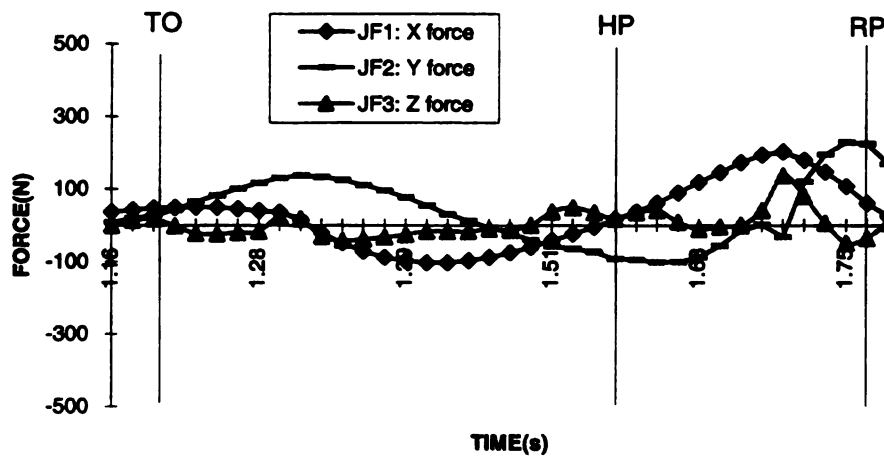


Figure 4.13b. Resultant joint force at the shoulder for the change-up pitch for the middle school subject 1.

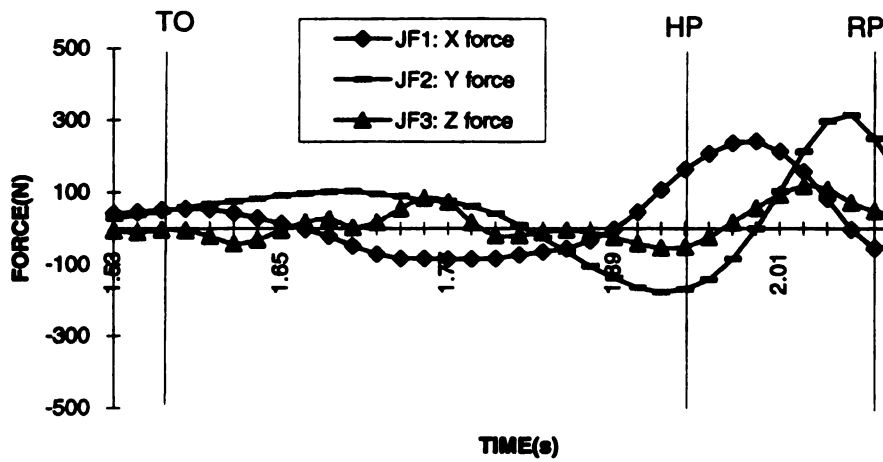


Figure 4.13c. Resultant joint force at the shoulder for the fast pitch for the high school subject 5.

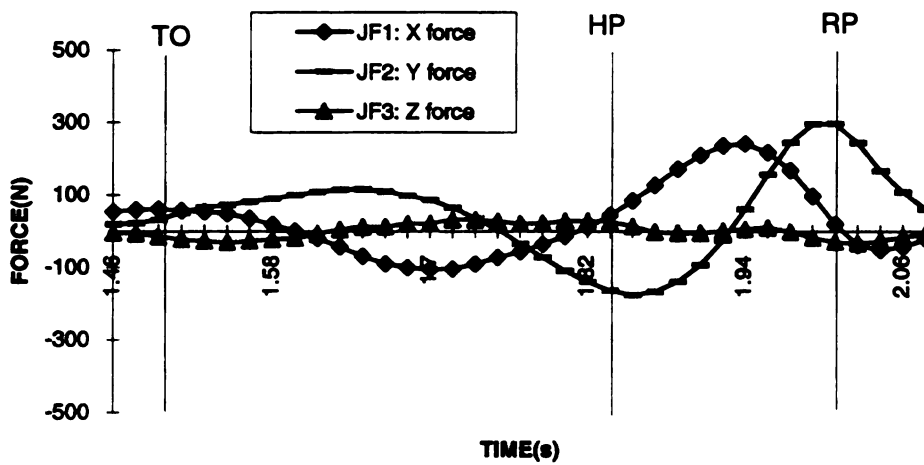


Figure 4.13d. Resultant joint force at the shoulder for the change-up pitch for the high school subject 5.

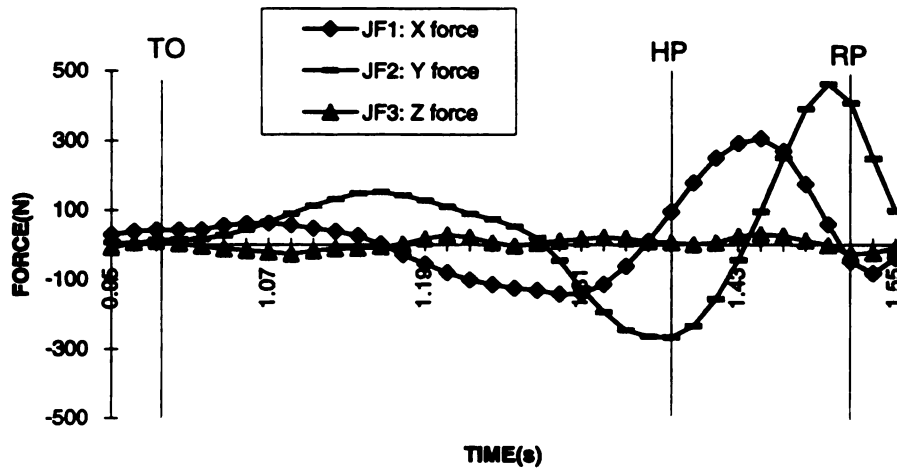


Figure 4.13e. Resultant joint force at the shoulder for the fast pitch for the college subject 4.

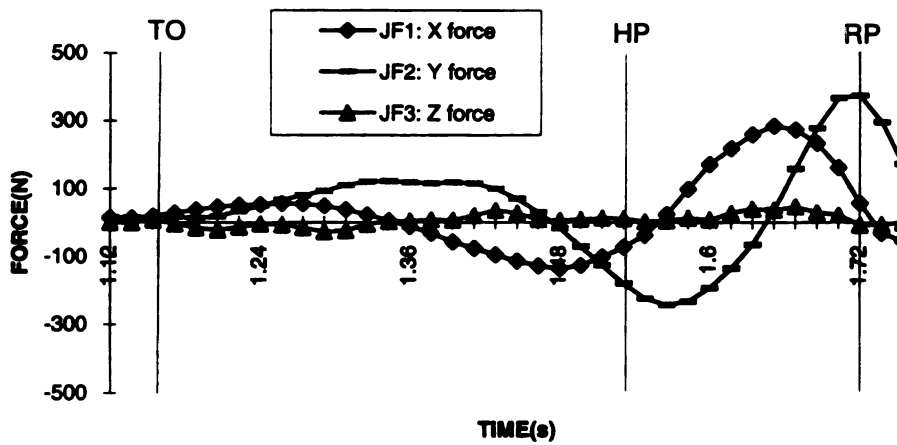


Figure 4.13f. Resultant joint force at the shoulder for the change-up pitch for the college subject 4.

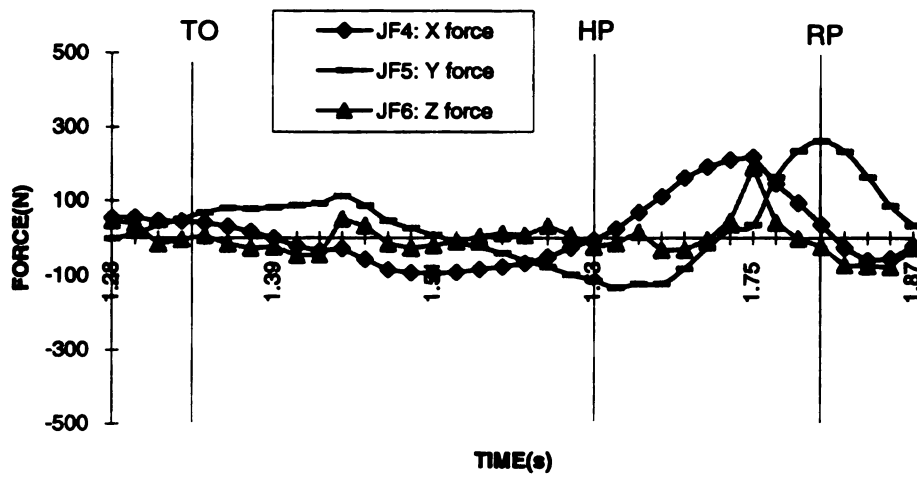


Figure 4.14a. Resultant joint force at the elbow for the fast pitch for the middle school subject 1.

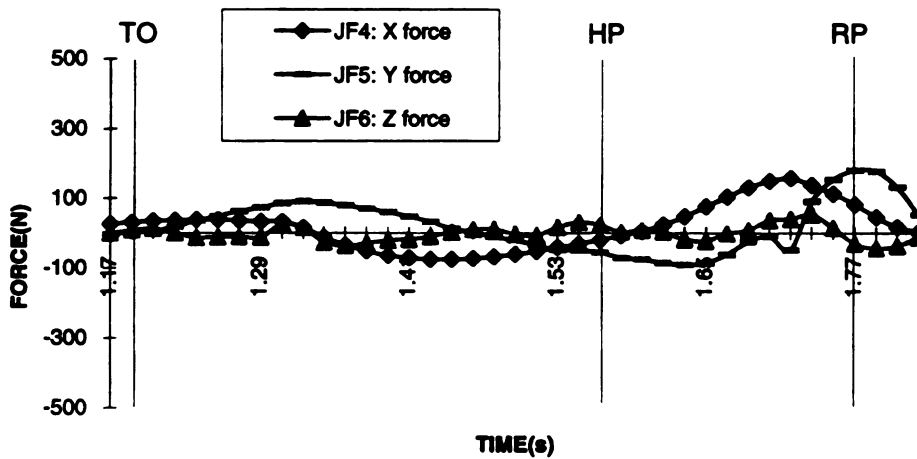


Figure 4.14b. Resultant joint force at the elbow for the change-up pitch for the middle school subject 1.

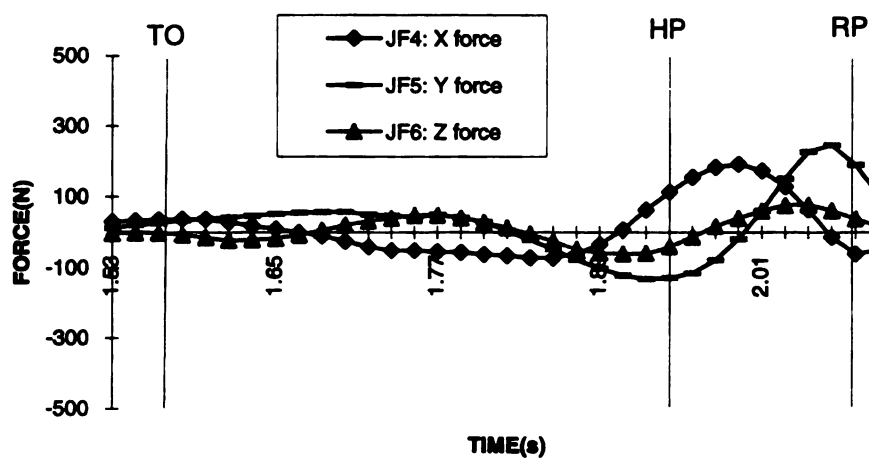


Figure 4.14c. Resultant joint force at the elbow for the fast pitch for the high school subject 5.

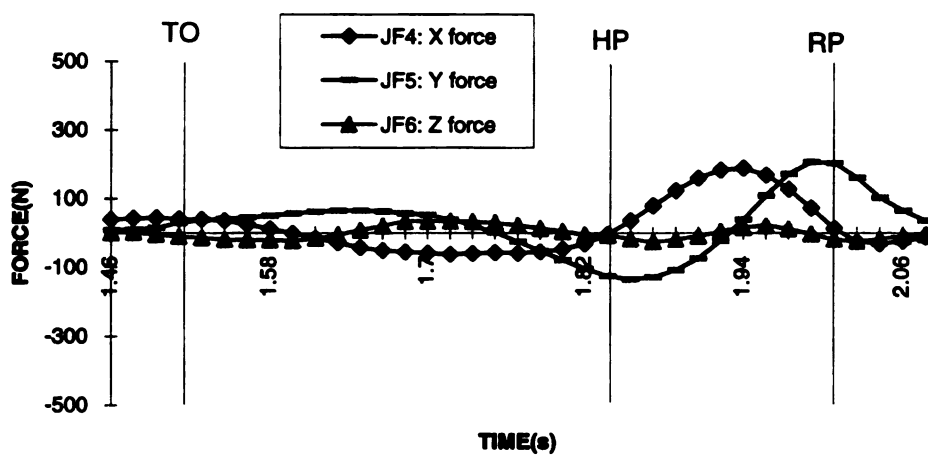


Figure 4.14d. Resultant joint force at the elbow for the change-up pitch for the high school subject 5.

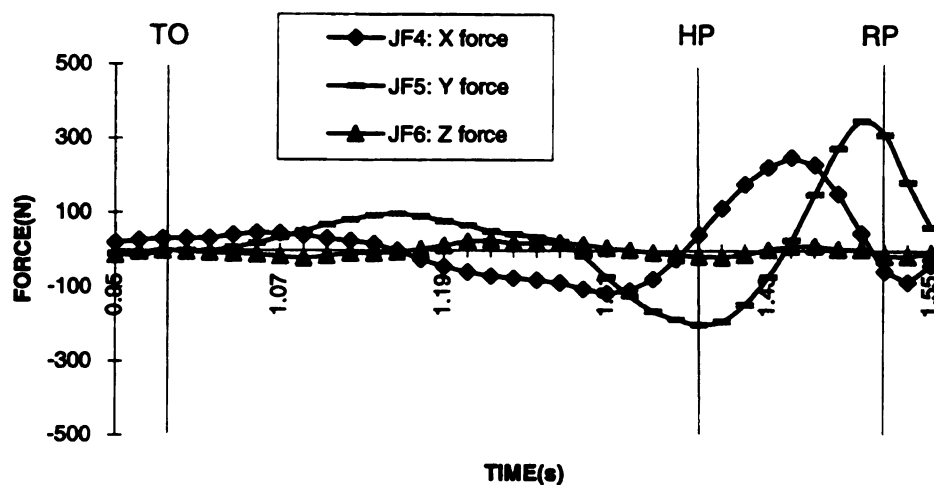


Figure 4.14e. Resultant joint force at the elbow for the fast pitch for the college subject 4.

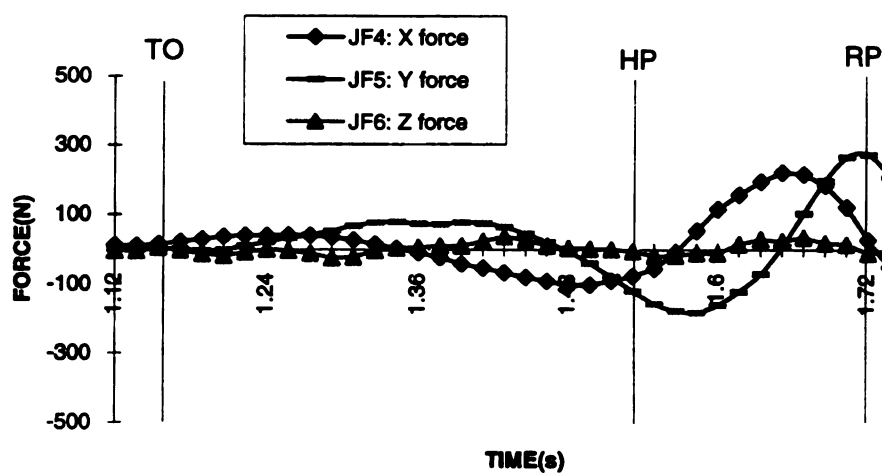


Figure 4.14f. Resultant joint force at the elbow for the change-up pitch for the college subject 4.

a positive value in the middle of the execution phase, followed by negative value until the point of the ball release. JF3 for the change-up pitch in the middle school was also similar. JF3 of the high school subject 5 for the fast pitch showed mostly positive values during the execution phase, but for the change-up remained roughly constant. JF3 of the college subject 4 for the fast and change-up pitches remained almost constant throughout the execution phase.

The three components (X force (JF4), Y force (JF5), and Z force (JF6)) of resultant joint forces at the elbow are shown in Figure 4.14. The patterns of these forces at the elbow for the fast and change-up pitches are similar to those shown Figure 4.13 for the shoulder.

The average values of the resultant joint forces at the shoulder throughout the execution phase are reported in Appendix B9. The average joint forces (JF1, JF2, and JF3) at shoulder during the execution phase for the fast pitch were 114.12 ± 31.84 N, 86.34 ± 26.08 N, and 20.10 ± 13.73 N for the middle school subjects; 155.99 ± 50.95 N, 70.22 ± 50.46 N, and 24.60 ± 24.39 N for the high school subjects; and 152.74 ± 41.28 N, 66.95 ± 63.30 N, and 30.12 ± 24.97 N for the college subjects, respectively. Those for

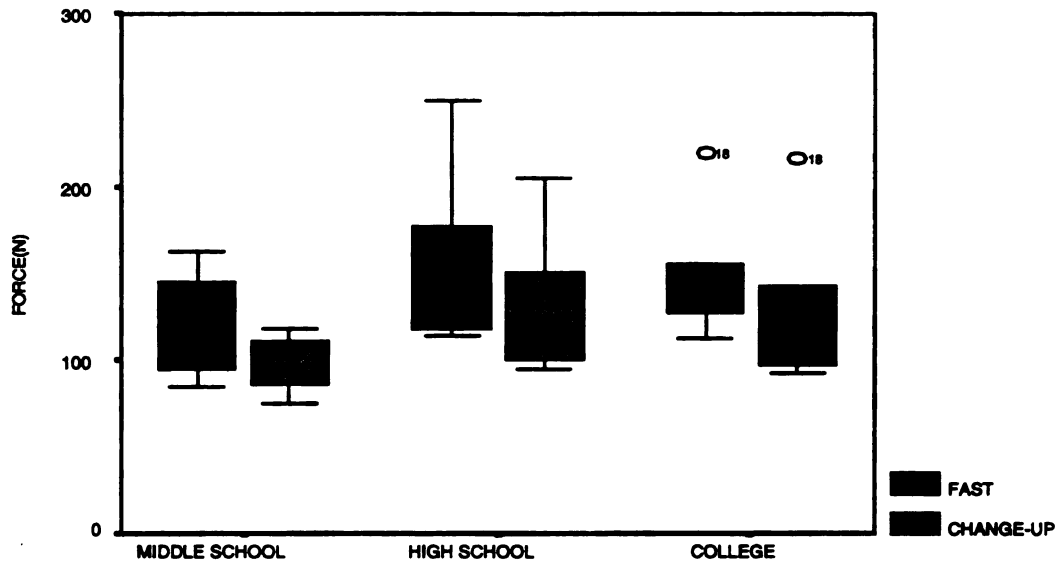


Figure 4.15. JF1 (X force) at the shoulder during the execution phase.

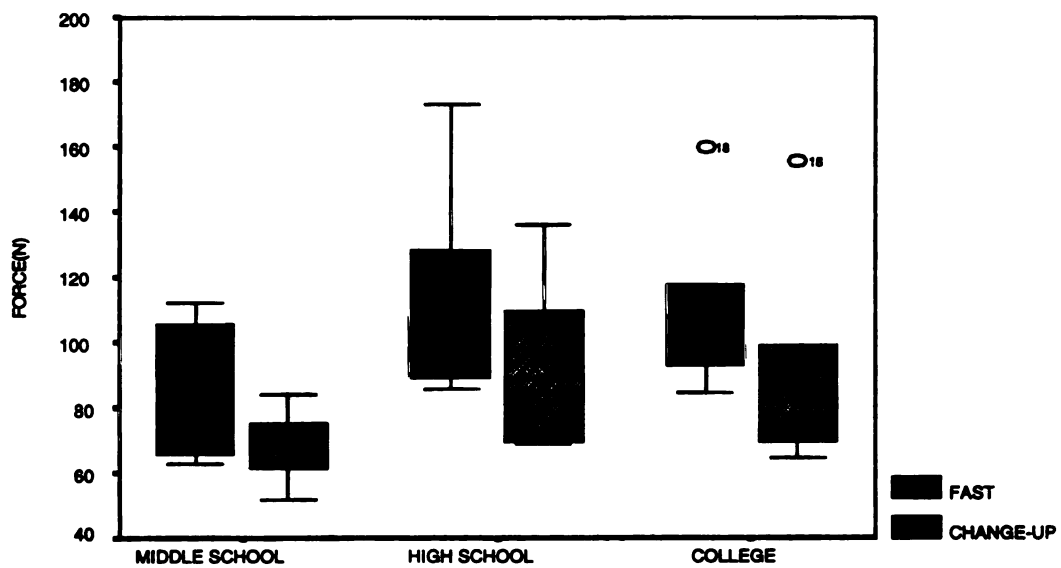


Figure 4.16. JF4 (X force) at the elbow during the execution phase.

change-up pitch were 97.55 ± 16.94 N, 48.08 ± 17.71 N, and 14.76 ± 7.88 N for the middle school subjects; 133.62 ± 41.12 N, 49.09 ± 29.65 N, and 15.28 ± 15.73 N for the high school subjects; and 131.93 ± 51.41 N, 52.03 ± 41.35 N, and 36.71 ± 17.78 N for the college subjects, respectively.

To consolidate these results into a comparative analysis of the three groups for the fast and change-up pitches, JF1 was examined. JF1 is in the intended direction of the pitch and is useful to analyze its impact on the ball velocity. Statistically, there was no significant difference in JF1 among the three groups, but significant difference was found between two styles of pitches ($P < .01$) (see Appendix B9). From Figure 4.15, it is evident that the average JF1 at the shoulder throughout the execution phase for fast pitch was higher than that for the change-up pitch among the three groups. The mean data indicates that for the fast pitch, the average JF1 for the shoulder of the middle school subjects was the smallest. The average JF1 for the shoulder in the high school and college subjects was similar. Also, in change-up pitch, a similar trend was shown as in the case of the fast pitch. A similar relationship was evident in the change-up pitch.

The average values of the resultant joint forces at the elbow throughout the execution phase are shown in Appendix B10. The average joint forces (X force (JF4), Y force (JF5), and Z force (JF6)) at the elbow throughout the execution phase for the fast pitch were 81.81 ± 21.31 N, 52.99 ± 18.27 N, and 11.51 ± 9.34 N for the middle school subjects; 111.52 ± 33.75 N, 43.42 ± 36.52 N, and 9.85 ± 19.88 N for the high school subjects; and 112.12 ± 29.76 N, 37.58 ± 41.80 N, and 12.60 ± 14.69 N for the college subjects, respectively. Those for the change-up pitch were 68.48 ± 11.39 N, 26.83 ± 11.50 N, and 7.27 ± 3.73 N for the middle school subjects; 93.48 ± 26.92 N, 26.09 ± 17.41 N, and 5.45 ± 9.91 N for the high school subjects; and 93.43 ± 37.53 N, 28.26 ± 27.47 N, and 17.21 ± 8.89 N for the college subjects, respectively.

To consolidate these results into differences among the three groups for the fast and change-up pitches, JF4 was examined to assess its impact on ball velocity, as JF1 was used in the case of the shoulder. Statistically, there was no significant difference in JF4 among the three groups, but significant differences were found between two styles of pitches ($P < .05$) (see Appendix B10). From Figure 4.16, the average JF4 at the elbow throughout the execution phase for

the fast pitch was higher than those for the change-up pitch among the three groups. The mean data indicates that for the fast pitch, the average JF4 for the elbow of the middle school subjects was the smallest. The average JF4 for the elbow in the high school and college subjects was similar. A similar relationship was evident in the change-up pitch shown as in the fast pitch.

Resultant Joint Torques

The graphs of the three components (X torque (JT1) about X axis, Y torque (JT2) about Y axis, and Z torque (JT3) about Z axis) of the resultant joint torque at the shoulder for three representative subjects (middle school subject 4, high school subject 1, and college subject 4) are shown in Figure 4.17. The patterns of JT1, JT2, and JT3 during the execution phase in each group for the fast and change-up pitches were similar. The positive value of the curve represented flexion torque at the joint and the negative value of the curve represented an extension torque at the joint. JT1 component followed a similar pattern in most subjects for the fast and change-up pitches. It had positive value from the later part of the preparation phase to the early part of the execution phase in most subjects. It had negative value in the middle of the execution phase,

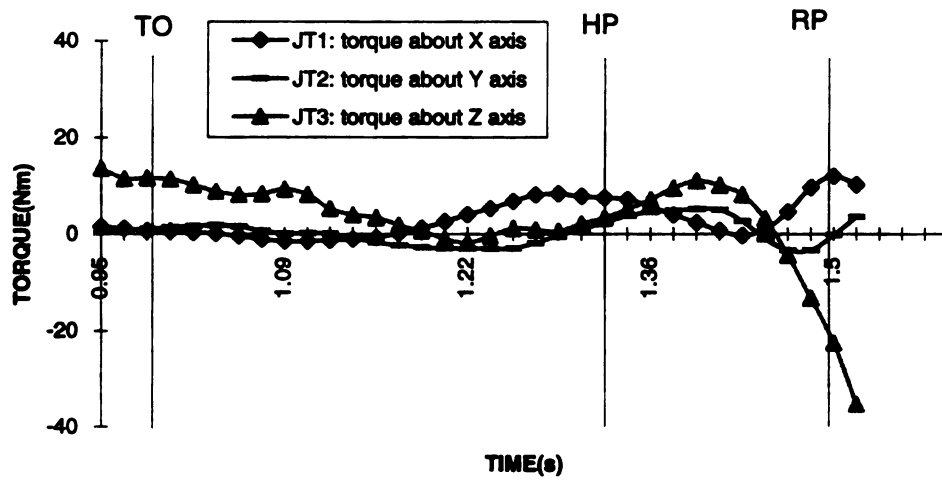


Figure 4.17a. Resultant joint torque at the shoulder for the fast pitch for the middle school subject 4.

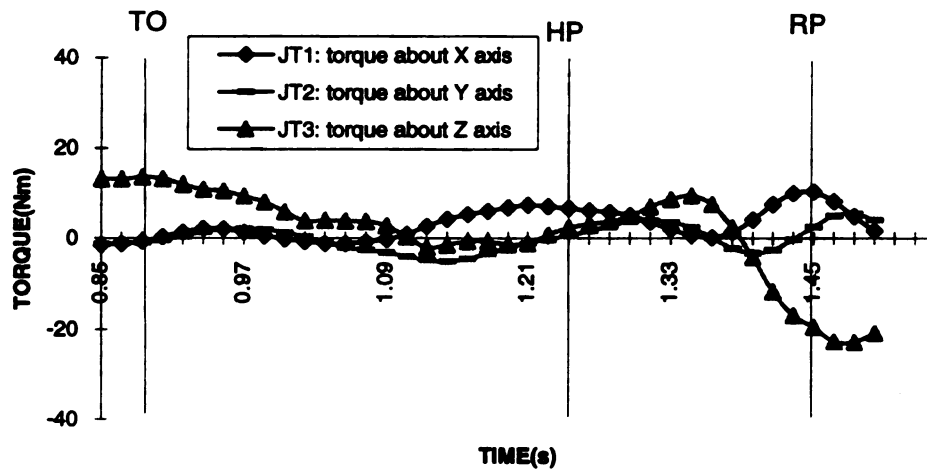


Figure 4.17b. Resultant joint torque at the shoulder for the change-up pitch for the middle school subject 4.

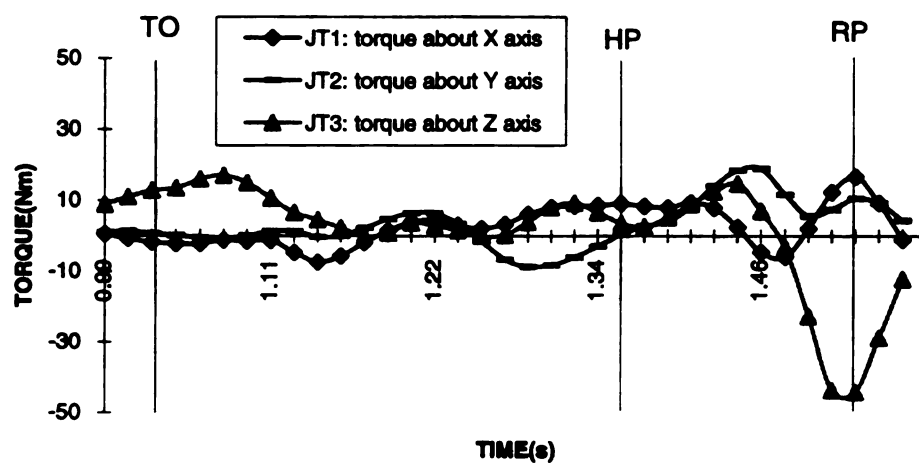


Figure 4.17c. Resultant joint torque at the shoulder for the fast for the high school subject 1.

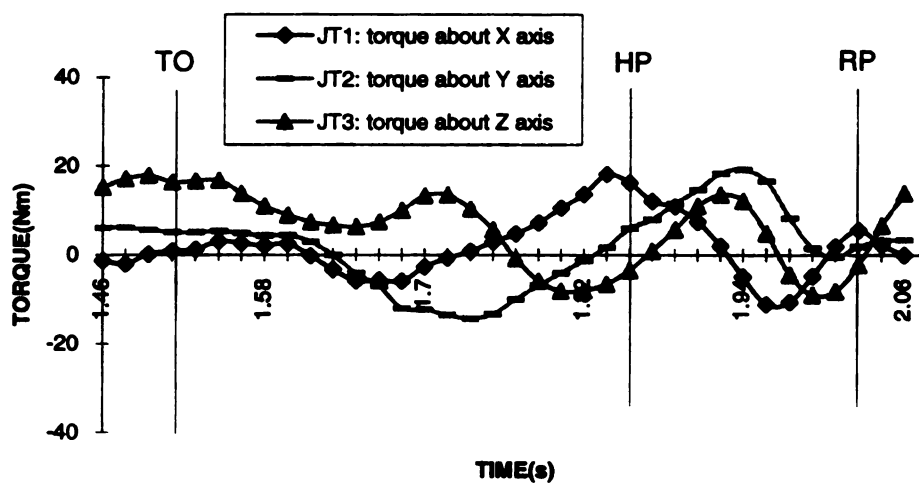


Figure 4.17d. Resultant joint torque at the shoulder for the change-up pitch for the high school subject 1.

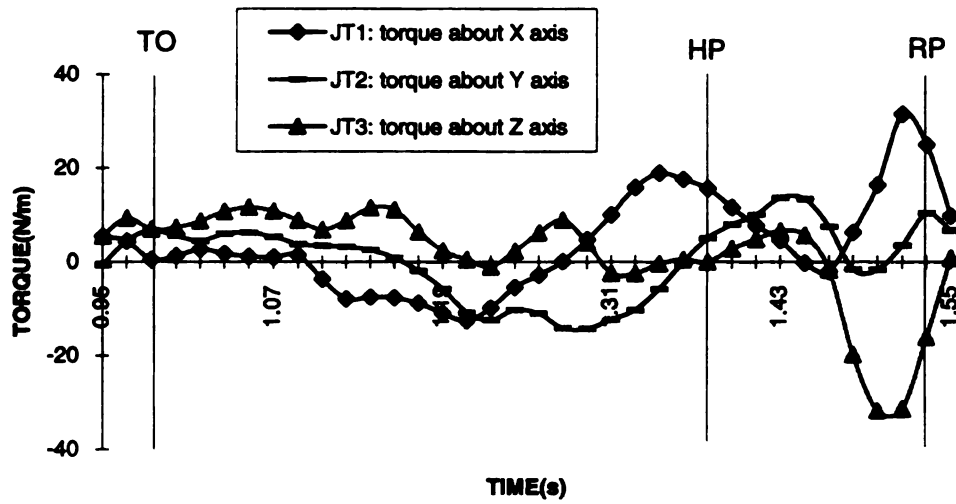


Figure 4.17e. Resultant joint torque at the shoulder for the fast pitch for the college subject 4.

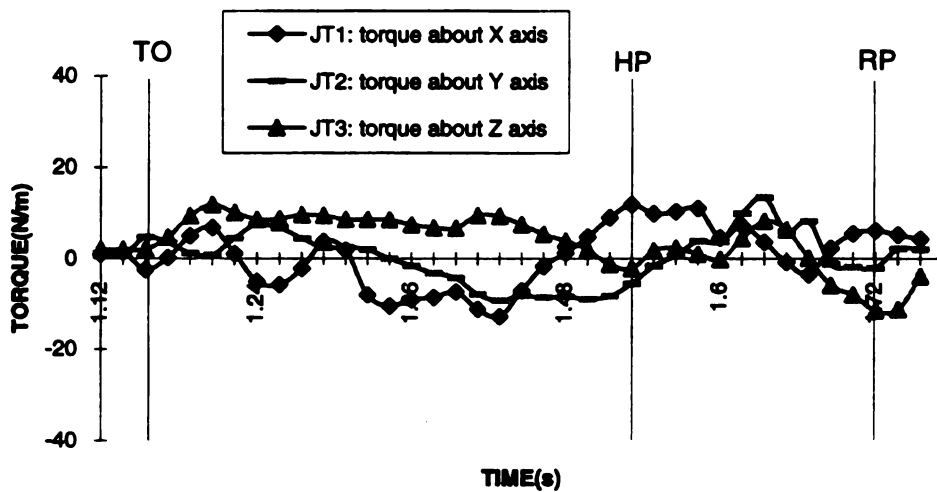


Figure 4.17f. Resultant joint torque at the shoulder for the change-up pitch for the college subject 4.

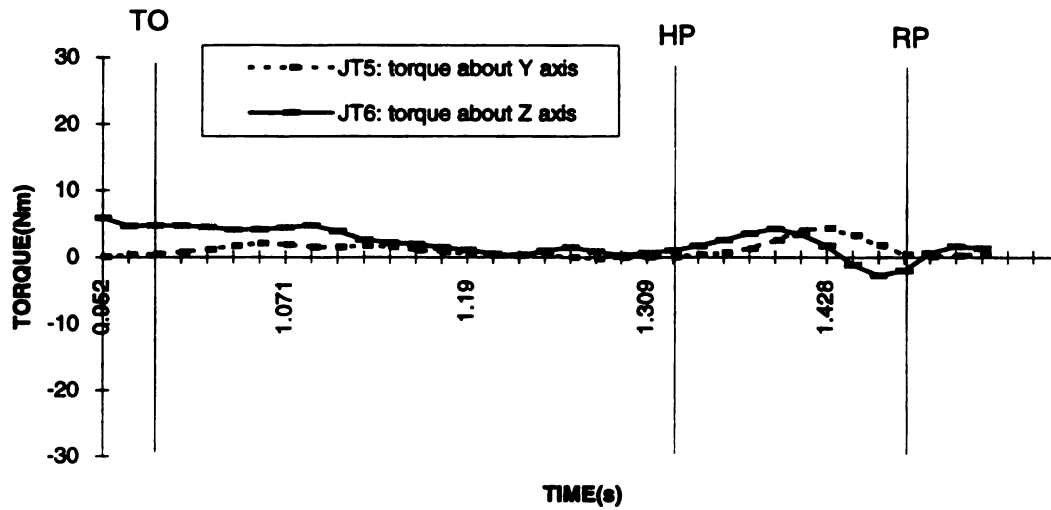


Figure 4.18a. Resultant joint torque at the elbow for the fast for the middle school subject 4.

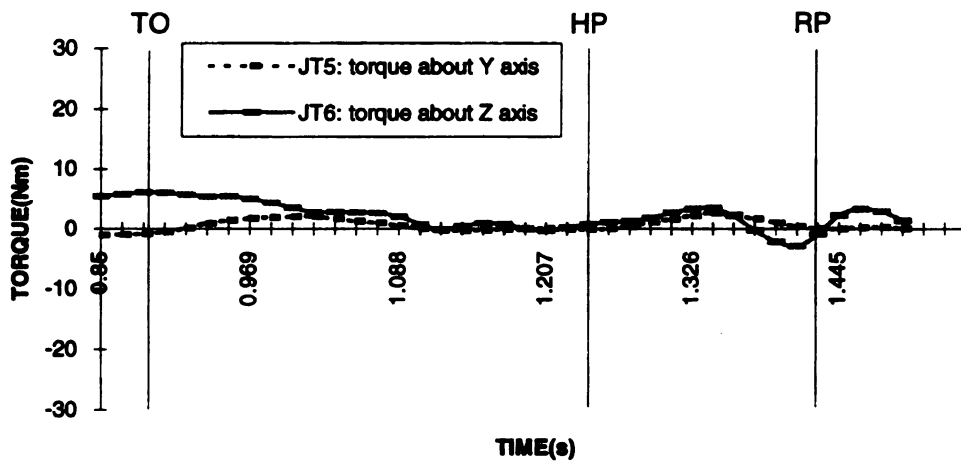


Figure 4.18b. Resultant joint torque at the elbow for the change-up pitch for the middle school subject 4.

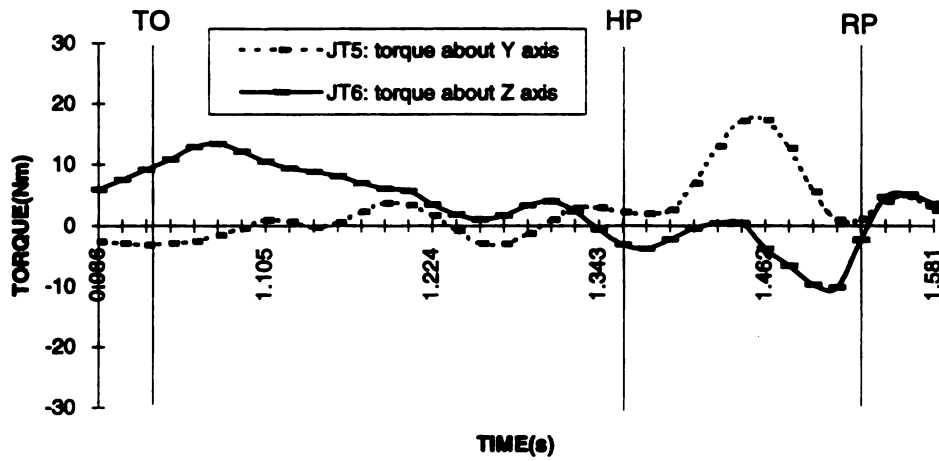


Figure 4.18c. Resultant joint torque at the elbow for the fast pitch for the high school subject 1.

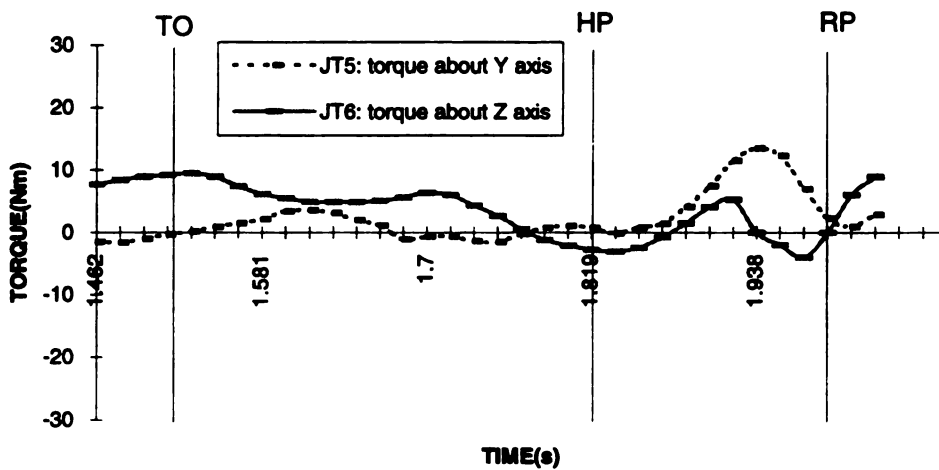


Figure 4.18d. Resultant joint torque at the elbow for the change-up pitch for the high school subject 1.

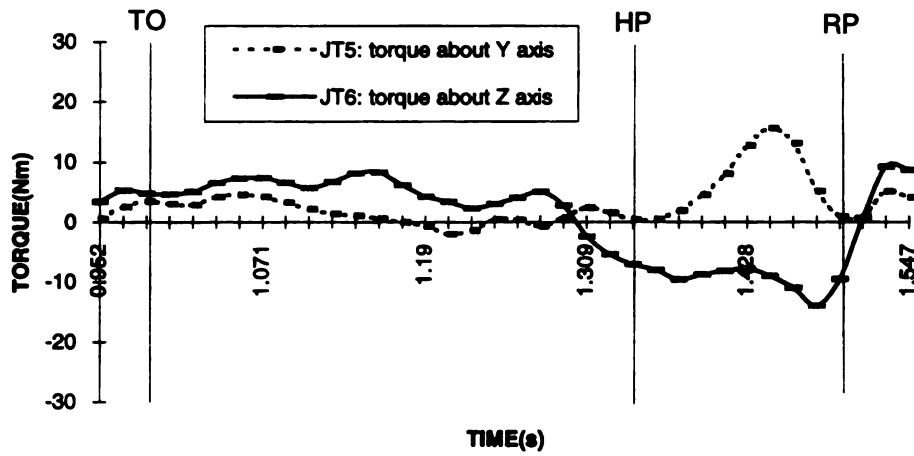


Figure 4.18e. Resultant joint torque at the elbow for the fast pitch for the college subject 4.

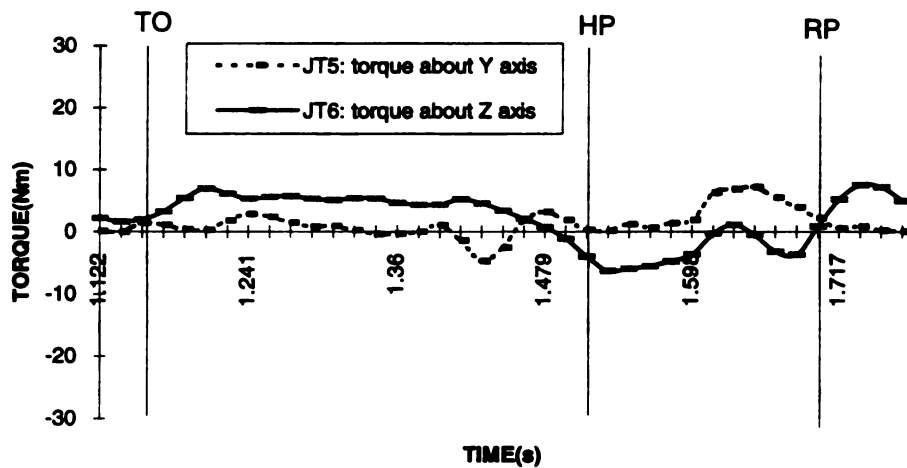


Figure 4.18f. Resultant joint torque at the elbow for the change-up pitch for the college subject 4.

and finally was positive throughout the rest of the execution phase.

The patterns of JT2 were similar among the three subjects. The middle school subject 4, for the fast and change-up pitches, showed positive values until the middle part of the execution phase, and then negative values around the release point. Also, the college subject 4 showed similar patterns. The high school subject 5 for the fast and change-up pitches, however, maintained the positive value throughout the execution phase.

The patterns of JT3 for both fast and change-up pitches were similar in most subjects among the three groups. Figure 4.17 showed values of small magnitudes during the later part of the preparation phase and the beginning of the execution phase. Then, JT3 showed positive values during the middle of the execution phase. Finally, it showed a considerable negative value around the time of ball release.

The graphs of the two components (Y torque (JT5) about Y axis and Z torque (JT6) about Z axis) of the resultant joint torque at the elbow for the fast and change-up pitches for three representative subjects (middle school subject 4, high school subject 1, and college subject 4) are reported in Figure 4.18. The patterns of JT5 and JT6 component were similar in most subjects.

The X torque value of the pronation-supination of the forearm (JT4) was not analyzed in this study. This was due in part to the fact that the resultant torque exerted on the forearm segment about its longitudinal axis could not be measured.

JT5 component (valgus-varus) value remained small until the beginning of the execution phase. Then it reached maximum positive (varus) value around the middle part of the execution phase and maintained the positive value throughout the rest of execution phase.

The pattern of JT6 was also similar among the subjects. The middle school subject 4, for the fast and change-up pitches, showed positive value (extension torque) during the middle of the execution phase, then negative value (flexion torque) throughout the rest of the execution phase. The high school subject 1, for the fast pitch, had mostly negative value during the execution phase, but for the change-up pitch had negative values around the beginning of the execution phase, then positive value until the middle, and negative values during the rest of the execution phase. The college subject 4, for fast and change-up pitches, had mostly negative values during the execution phase.

The average values of the resultant joint torques at the shoulder during the execution phase are reported in Appendix

B11. The average joint torques, JT1, JT2, and JT3, at the shoulder during the execution phase for the fast pitches were 2.48 ± 3.87 Nm, 5.37 ± 4.98 Nm, and -5.52 ± 4.67 Nm for the middle school subjects, 3.17 ± 5.57 Nm, 6.68 ± 5.03 Nm, and -6.10 ± 1.50 Nm for the high school subjects, and 2.49 ± 6.51 Nm, 9.67 ± 4.75 Nm, and -7.39 ± 7.04 Nm for the college subjects, respectively. Those for the change-up pitch were 3.15 ± 2.27 Nm, 2.64 ± 3.60 Nm, and -2.54 ± 4.23 Nm for the middle school subjects, 2.58 ± 3.48 Nm, 3.55 ± 3.29 Nm, and -3.32 ± 3.20 Nm for the high school subjects, and 2.27 ± 3.64 Nm, 7.06 ± 3.34 Nm, and -5.45 ± 4.86 Nm for the college subjects, respectively.

The average values of the resultant joint torques at the elbow during the execution phase are reported in Appendix B12. The average joint torques JT5 and JT6 at the elbow during the execution phase for the fast pitch were 3.01 ± 1.85 Nm and -0.97 ± 1.14 Nm for the middle school subjects and 4.00 ± 3.18 Nm and -2.07 ± 1.38 Nm for the high school subjects and 5.10 ± 2.56 Nm and -5.33 ± 2.93 Nm for the college subjects, respectively. Those for the change-up pitch were 1.86 ± 1.80 Nm and -0.50 ± 1.40 Nm for the middle school subjects and 2.72 ± 2.75 Nm and -1.25 ± 2.88 Nm for

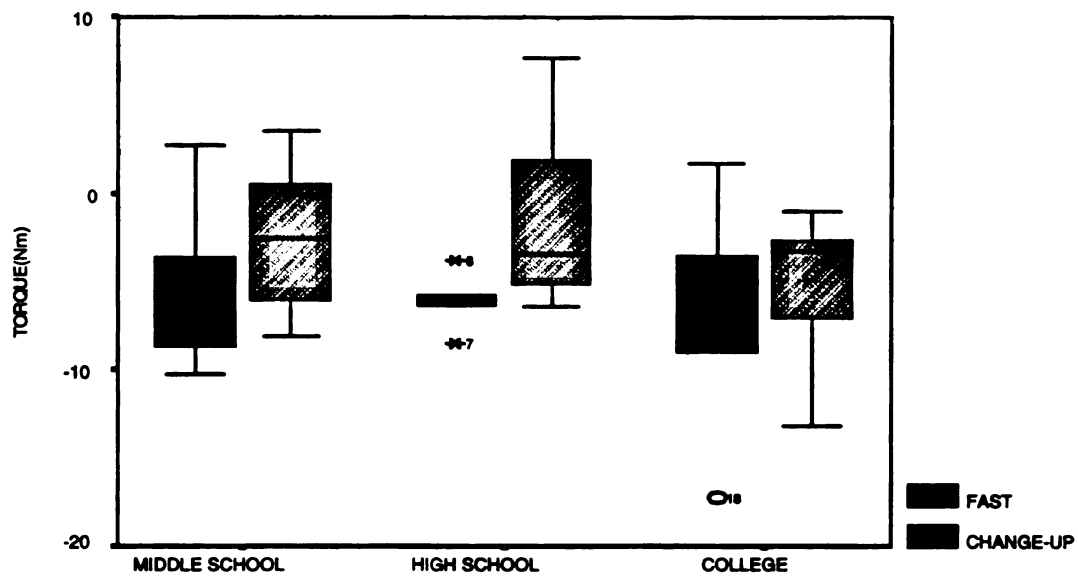


Figure 4.19. Flexion-extension torque (JT3) at the shoulder during the execution phase.

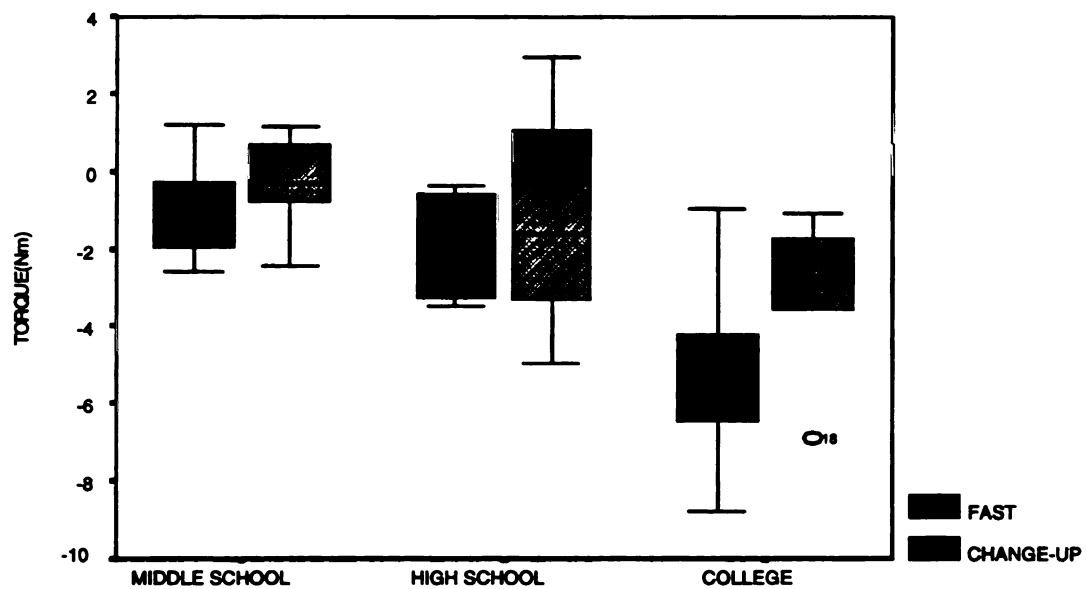


Figure 4.20. Flexion-extension torque (JT6) at the elbow during the execution phase.

the high school subjects and 3.25 ± 1.50 Nm and -3.03 ± 2.33 Nm for the college subjects, respectively.

Statistically, there was no significant difference in JT3 at the shoulder among the three groups, but significant differences were found between two styles of pitches. Also, in JT6 at the elbow joint there were significant differences among the three groups and between two styles of pitches ($P < .05$) (see Appendix B11 and B12). From Figures 4.19 and 4.20, it is evident that the mean resultant torques at the shoulder and elbow during the execution phase for the fast pitches among the three groups were higher than those for the change-up pitches. But unlike the statistical result, the mean resultant torques of the shoulder and elbow for both fast and change-up pitches increased from the middle school to college.

Ground Reaction Forces

The graphs of ground reaction forces (X force (GF2), and Y force (GF3), and Z force (GF1)) for one subject representing each group are shown in Figure 4.21. The force curves for subject 2 in the middle school, as shown in Figure 4.21, illustrates that GF3 increased while GF2 decrease in magnitude. This occurs during the windup when the weight is exerted on the front foot, and the body mass is actually moving downward on this foot. The peak GF3 for

the fast pitch is reached very close to the highest point of the shoulder, and is likely caused by forceful extension of the joints of the right leg as the subject drives her body upward and forward into the pitching motion. This forceful hip and knee extension and ankle plantar flexion is also accompanied by the rapid and forceful rotation of the body around the left hip. These forceful movements are accompanied by a rapid adduction and flexion of the arm at the shoulder--all of which produce downward forces causing the peak GF3 at this point. The peak GF3 for the change-up pitch, however, is reached well before the release of the ball.

The ground reaction force curves for the high school subject 5, as shown in Figure 4.21, for the fast and the change-up pitches were similar. The peak GF3 for the fast and change-up pitches occurred very early, approximately 0.41 second prior to the release of the ball.

The pattern of GF3 for the fast and change-up pitches in the college subject 5 were similar. The shapes of GF3 look like a parabola. These are unlike the ground reaction force curves exhibited by the middle school subject 2 and the high school subject 5. This indicates that highly skilled performers may exert force more rapidly in a similar pattern of movement. The leaping style pitching, exhibited

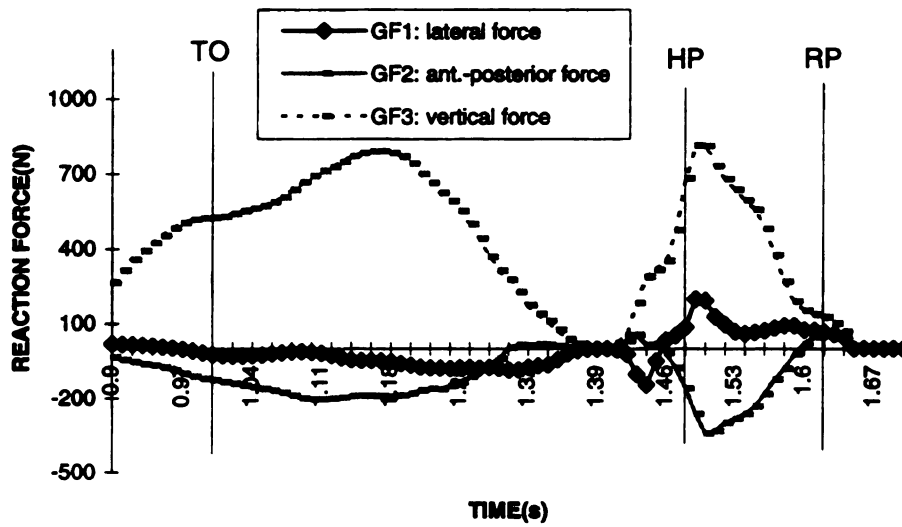


Figure 4.21a. Ground reaction forces for a fast pitch delivered by middle school subject 2.

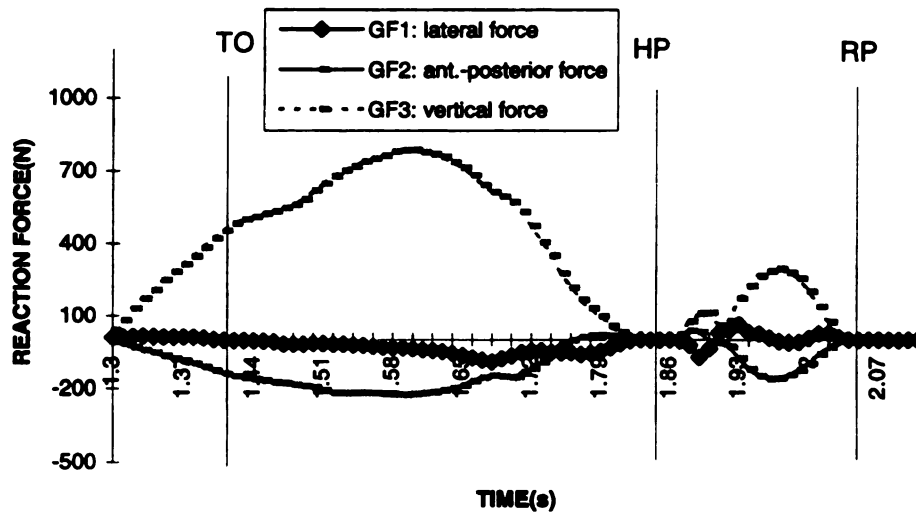


Figure 4.21b. Ground reaction forces for a change-up pitch delivered by middle school subject 2.

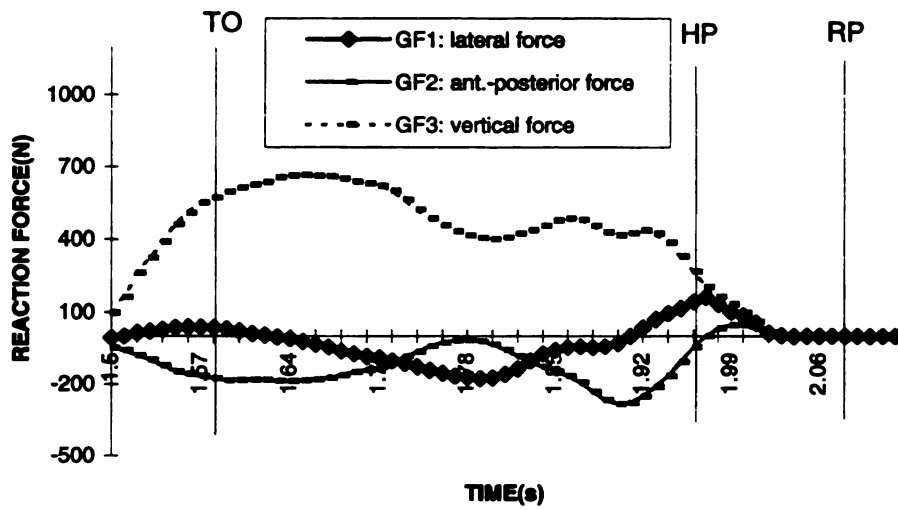


Figure 4.21c. Ground reaction forces for a fast pitch delivered by high school subject 5.

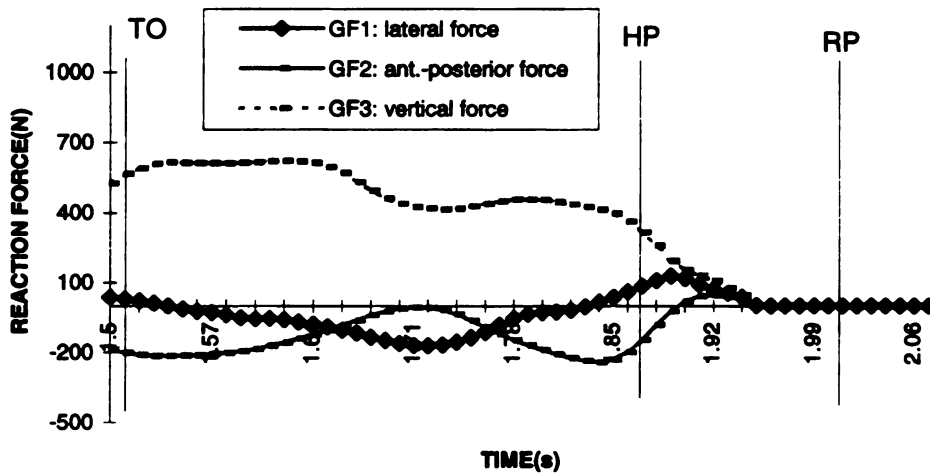


Figure 4.21d. Ground reaction forces for a change-up pitch delivered by high school subject 5.

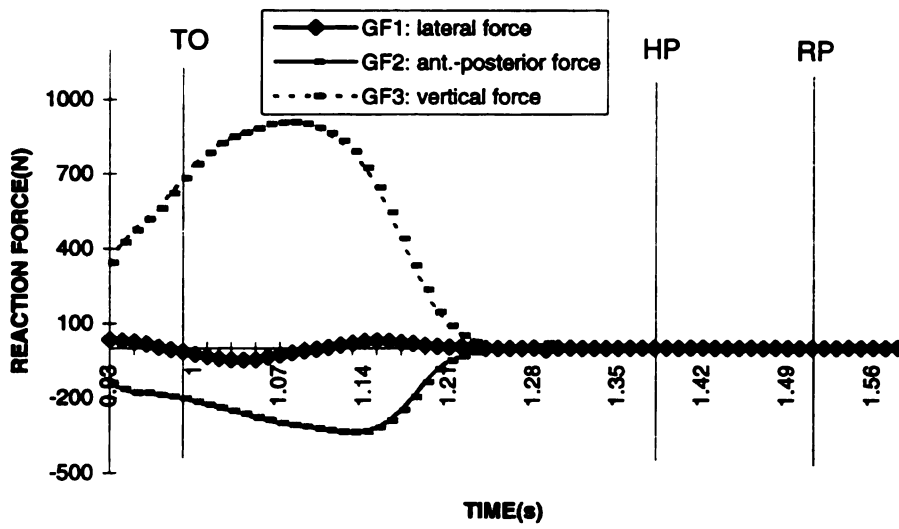


Figure 4.21e. Ground reaction forces for a fast pitch delivered by college subject 4.

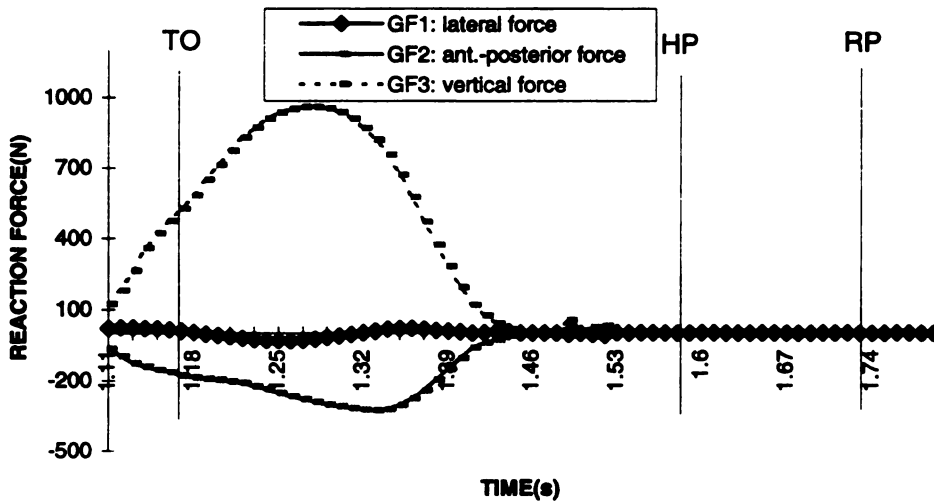


Figure 4.21f. Ground reaction forces for a change-up pitch delivered by college subject 4.

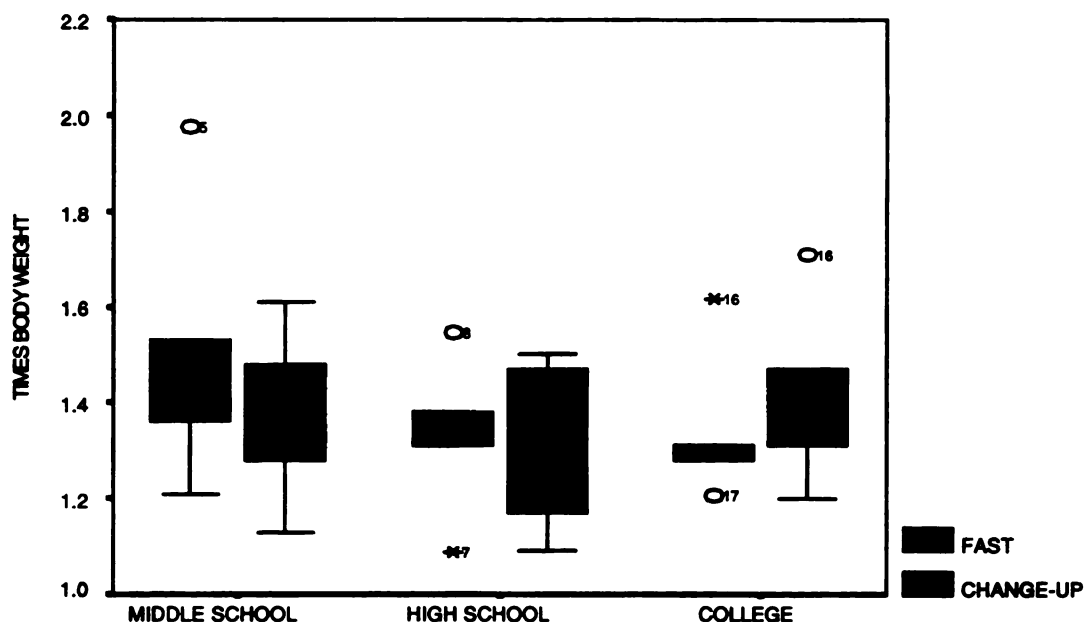


Figure 4.22. Normalized maximum Y ground reaction force (GF3).

by some of the college pitchers, may have caused differences in the force curves because the pivot foot left the force platform prior to the time the arm reached its highest point. This is evident in Figure 4.21e-f.

The means of the maximum GF3 throughout the pitching motion the middle school, high school, and college subjects are reported in Appendix B13. The means of the maximum GF3 for the fast and change-up pitches were 736.72 ± 240 N and 675.00 ± 182.64 N in the middle school, 741.46 ± 144.17 N

and 727.04 ± 226.41 N in the high school, and 814.12 ± 196.28 N and 866.44 ± 189.48 N in the college subjects, respectively.

Statistically, there was no significant difference in the peak vertical ground reaction force between two styles of pitch and also among the three groups. From Figure 4.22, it is evident that the normalized peak GF3 for the fast and change-up pitches for the high school subjects was similar and only slightly different in the middle school and college subjects. Unlike the statistical result, the mean data indicates that The normalized peak value of the Y ground reaction force for the fast pitch in the middle school subjects was higher than that for the change-up pitch, but in the college subjects was less than that for the change-up pitch.

It is evident from the vertical ground reaction force records (see Appendix B13) that there was relatively little difference in the mean maximum Y ground reaction force in most subjects between the fast pitch and change-up pitches in the three groups. The results of the time of takeoff on the pivot foot from the force platform and the time of ball release indicates that the middle school subjects kept their pivot foot on the force platform until the ball was released, but the high school and college subjects took

their pivot foot off force platform before the ball was released. Also, the period between the time of the maximum Y force and the time of ball release showed that the middle school subjects reached maximum force very close to the time of release of the ball, and in the high school and college subjects, this occurred well before the release of the ball.

CHAPTER V

DISCUSSION AND CONCLUSIONS

This chapter contains an interpretation of the results presented in the previous chapter. This interpretation includes comparisons of the commonalties and differences in the fast and change-up pitches among middle school, high school, and college subjects. In addition, relationships of the findings to statements, regarding softball pitching motion, in the literature are discussed in an effort to compare the evidence of this study to past research and theories.

Temporal Analysis

Stride foot contact with the ground always occurred before release, usually at a point when the pitching arm approached the horizontal position behind the body. The actual time before release, that stride foot contact occurred, ranged between .112 to .147 s, depending on the subject and the type of pitch. This finding supports Werner (1994b), Guenzler (1979), and Cooper and Glassow (1976) descriptions of the timing of stride foot contact with the ground. The mean time for the fast pitch from the stride foot's takeoff from the ground to the point of

ball release is less than that obtained for the change-up pitches among the three groups. For the population studied, the mean time, from the highest point of the arm to the release of the ball, ranged between .155 and .170 s for the fast pitches and .184 to .198 s for the change-up pitches. The entire movement pattern carried out from the time the stride foot touched down until the ball was released took only about 0.1 s. These results were also similar to other reports found in the literature (Werner, 1994a; Guenzler, 1979). This timing data supports the idea that the windmill pitch is a highly dynamic activity. The windmill pitching motion takes a relatively short time period, requires extremely high speeds of upper extremity movement, and, therefore, a high degree of muscular contraction and coordination.

Ball Velocity

The average ball velocity for the fast pitch was 21.22 m/s for the middle school subjects, 22.35 m/s for the high school subjects, and 23.39 m/s for the college subjects. Compared to previous studies of female college pitchers, as reported by Kinne (1985) and Werner (1994a), the mean velocity of the fast pitch was similar to the mean of the fast pitch of the college subjects in the current study. But no studies of the windmill pitching motion of middle

school or high school subjects were found. In the current study, the means for the change-up pitches were 18.34 m/s for the middle school subjects, 17.14 m/s for the high school subjects, and 18.46 m/s for the college subjects. The mean velocities of the fast pitch for each group were greater than those reported in Guenzler's (1979) study. Most studies of the softball windmill pitching motion have not assessed the ball velocity of the change-up pitch. The differences of the ball velocity between the fast and change-up pitches for the middle school subjects were small compared with the other two groups. The data indicates that middle school subjects in this study seemed less skilled than high school and college subjects in controlling the velocity of the change-up ball.

Stride Length

The mean normalized stride lengths among the three groups in the current study for both fast and change-up pitches were much larger than those reported in previous studies (Werner, 1994; Kinne, 1985; Guenzler, 1979). The stride lengths for the middle school subjects for the fast and change-up pitches were consistent, but the stride lengths for one high school subject and three college subjects were over 100 percent of their height. Those subjects, who demonstrated greater stride lengths, tended

to exhibit a leaping motion while they pitched the ball. The stride lengths of these subjects increased the mean of the stride length for each group. It should be noted that the increased stride length did not have a major effect on the ball velocity for both styles of pitches. In fact, as in previous studies (Bridges, 1982; Werner, 1994), a conclusion of this study, if these few subjects were not included, is that stride lengths around 80 to 90 percent of height could be considered appropriate for a good pitching motion. Also, the current study shows that the stride length for the two pitches among the three groups was similar.

Contributions to the Ball Velocity

The factors that contributed to the velocity of the ball for the fast and change-up pitches were similar among the three groups. From the results of this study, it is apparent that the major factors that contributed to the velocity of the ball for the fast and change-up pitches were the flexion of the shoulder and elbow. According to Cooper et al. (1988) and Gowitzke and Milner (1982), shoulder and wrist flexion were the major factors that contributed to ball velocity. These researchers did not, however, investigate the elbow flexion. The current study has demonstrated that elbow flexion was a major contributor

to the ball velocity more so than wrist flexion. Also, hip rotation was an important factor in enhancing ball velocity. The data showed that hip rotation was tended to increase from the middle school to college subjects. Also, the data indicates that the high school and college subjects demonstrated greater hip rotation when pitching fast balls than change-up balls. But, this process was reversed in the middle school subjects. The ball velocity of the middle school subjects was less than the other two groups, the implication being that their pitching motion was not well coordinated.

Angular Displacement

The patterns for angular displacement of abduction-adduction (JD1), horizontal abduction-adduction (JD2), and flexion-extension (JD3) at the shoulder were similar in each group of subjects for the fast and change-up pitches. The angular displacement of flexion-extension (JD3) was consistent in most subjects. The mean orientation of JD3 of the arm for the fast pitch among the three groups at release was less than that for the change-up pitch. This result indicates that at release the shoulder for the change-up pitch was more flexed than in the fast pitch.

The patterns of the flexion-extension displacement of the forearm (JD4) in most subjects at release were similar

for the fast and change-up pitches. The mean of JD4 for the fast pitch among the three groups was less than that in the change-up pitch. The current result was similar to that reported by Werner (1994c). This finding indicates that the subjects for the change-up pitch at release tended to flex their elbow more. In terms of angular displacement of JD3 and JD4, the release point of the ball for the change-up pitch occurred at a more forward position of the arm than for the fast pitch. These results also showed some differences in angular displacement between the two pitches among the three groups, but the differences were not conclusive enough to establish a pattern.

Angular Velocity

The patterns of the flexion-extension velocity (JA3), the abduction-adduction (JA1), and the horizontal abduction-adduction (JA2) velocity at the shoulder during the execution phase for the fast and change-up pitches were similar among the three groups. This study focused more on the patterns of JA3 and JA4 (flexion-extension velocity at the elbow). It has been established that flexion-extension velocity is a most significant contributor to ball velocity (Chung, 1988). The current study demonstrated that the peak angular velocity of JA3 at the shoulder for the fast and change-up pitches was reached at

approximately the middle of the execution phase and the peak value of JA4 at the elbow was reached just prior to the release of the ball. This data implies that as the peak velocity for the arm was reached, the forearm began to rapidly increase in velocity. The other notable finding was that the peak angular velocity of the forearm occurred at almost the same instant as the release of the ball. This finding is in agreement with that of Alexander (1979), who also noted that a skilled performer will reach maximum angular velocity of the forearm segments at virtually the same instant as the ball release. The slowing down of the arm segments prior to release of the ball was demonstrated by Plagenhoef (1966) who also noted that the proximal segments slowed down prior to release of the ball in throwing skills. The angular velocity reduced in the arm prior to the release of the ball while, at the same time, the angular velocity of the forearm increased. This demonstrates that the flexion of the elbow is an important contributory factor to the ball velocity.

The mean peak angular velocity of JA3 for the fast pitch among the three groups was higher than that for the change-up pitch. For both fast and change-up pitches, the mean peak angular velocity of JA3 in the high school subjects was the highest among the three groups. The mean

peak angular velocity of JA4 for the fast pitch among the three groups was higher than that for the change-up pitch. For the fast pitch, the mean peak angular velocity of JA4 for the high school and college subjects was higher than that for the middle school subjects. Also, the change-up pitch showed similar results as the fast pitch, but in the change-up pitch the value of JA4 in the middle school subjects was higher than that in the high school subjects. The common pattern discovered in this analysis is that the high school and college subjects showed greater peak angular velocity than the middle school subjects in both styles of pitching. The greatest peak angular velocity and subsequent greater ball velocity was found in the top college pitchers than in the best pitchers from the other two groups.

Resultant Joint Forces

The patterns of the X force (JF1) and Y force (JF2), and Z force (JF3) at the shoulder were similar in most subjects for the fast and change-up pitches. JF1 reached maximum force around the middle of the execution phase. JF2 reached maximum force almost at the instant of the ball release.

The mean values of JF1, JF2, and JF3 at the shoulder during the execution phase for the fast pitch, among the

three groups, were higher than those for the change-up pitch. The mean of JF1 among the three groups for fast pitch was higher than for the change-up pitch. The mean of JF1 for the high school and college subjects for the fast pitch was higher than for the middle school subjects. Also, a similar relationship was evident for the change-up pitch. The mean value of JF1 among the three groups was much larger than the mean value of both JF2 and JF3. This result implies that JF1 seemed to be the most important factor in contributing to the ball velocity. When comparing the mean value of JF2 among the three groups for the fast pitch, the mean value for the college subjects was the smallest, followed by the high school subjects. These results indicate that more experienced pitchers had a small magnitude for JF2 and a large magnitude for JF1. For the change-up pitch, the mean value of JF2 for the college subjects was the highest, followed by the high school subjects. The large magnitude of the JF2 reduced the forward force of the arm (JF1), thereby reducing ball velocity in the change-up pitch.

The patterns of the three components of the resultant force at the elbow were similar to those shown at the shoulder. However, the magnitudes of the mean value of the three components were less than those at the shoulder.

The mean of JF4 at the elbow was examined for comparing the fast and change-up pitches among the three groups. The pattern of JF4 at the elbow was similar to that shown at the shoulder. But, the mean value was less than at the shoulder.

These results indicate that the acceleration of the pitching arm during the execution phase for the fast pitch was higher than that for the change pitch. The proximal segments have a considerably greater mass than the distal ones, which affect the magnitude of the resultant joint force. The factor that contributed to the difference in the force pattern was segment mass. The great mass of the college subjects as compared to the other two groups contributed to the higher force pattern they demonstrated.

Resultant Joint Torques

The patterns of the resultant joint torque X torque (JT1), Y torque (JT2), and Z torque (JT3)) at the shoulder were similar in most subjects for the fast and change-up pitches. The mean flexion-extension torque (JT3) was higher in the fast pitch than in the change-up pitch. Once again, during the execution phase, the value of the torque tended to increase from the middle school to the college. The resultant joint torque represents the sum of all the torques about the joint center exerted by the

proximal segment on the distal segment through the muscles, ligaments, bones, skin, nerves, blood vessels, etc. that connect the two segments. The most marked curves in the JT2 and JT3 are the large negative torques which represent the slowing down, or reversal of movement of the arm around the shoulder joint prior to the release. The magnitude of the torque indicates the extent of muscle contraction. The large negative torque at the shoulder joint was likely the result of the action of the extensor muscles of the shoulder, causing a reversal, or slowing down of this motion. It is likely that the shoulder flexors (pectoralis major, anterior deltoid, and long head of biceps) are most active relatively early in the action, and that this activity is reduced prior to the point of the release of the ball. At this point, the shoulder extensors are likely very active as seen in a reversal of the resultant torque at the shoulder joint. They cause a reduction in the angular velocity of this segment.

The patterns of the Y torque (JT5) and Z torque (JT6) at the elbow were similar. The pattern of JT5 shows a large positive torque prior to the point of ball release, which is representative of rapid flexion. The pattern of JT6 is the large negative torque around the point of ball release in most subjects. The large negative torque of

JF3 at the shoulder produced an accompanying negative torque of JT6 at the elbow, even though both of these joints are flexing at the point of release. This indicates that the dominant muscle group at the release of the ball was the shoulder extensors which were acting eccentrically as a brake to slow down the flexion of the arm at the shoulder joint. This is a very interesting finding because it had been common belief that the major force producing muscles in this skill acted strongly up to the point of release.

These findings indicate that an electromyographic analysis of the active muscles during the softball pitch would be useful to compare with the torque analysis. It would appear possible from this analysis that important muscle force in this skill may not be those of the agonist muscles to these movements, but rather those of the antagonists. Possibly in training highly skilled pitchers in the future, coaches should be training the shoulder extensors to act as a strong brake to this motion, rather than to work for a more forceful agonistic contraction.

Ground Reaction Forces

The patterns of the ground reaction forces (X force (GF2), Y force (GF3), and Z force (GF1)) for the fast and change-up pitches during the pitching motion were similar

in most subjects. The GF1 changed very little and remained stable. Generally, the GF2 decreased while the GF3 increased when the foot contacted the force platform for the fast and change-up pitches. The pattern of the GF3 was similar between the two pitches within the same subject, but not among all the subjects. The pitchers tended to reach maximum Y force for the fast and change-up pitches well before the ball was released. The normalized peak mean value of the Y ground reaction force for the fast and change-up pitches differed little among the three groups. The similarity in the vertical ground reaction force of the pivot foot among the three groups seems to indicate that the difference in ball velocity may not have been affected by the pivot foot in both styles of pitches.

The time gap between the period of reaching the maximum Y ground reaction force and the time of releasing the ball was different among the three groups. The time gap was narrow in the middle school subjects, but wider in the high school and college subjects. These results indicate that the middle school subjects tended to stay on their pivot foot until the ball was released; the high school and college subjects took their pivot foot off the force platform earlier. The faster transition from the pivot

foot to the stride foot results in a more forceful forward momentum increasing the potential velocity of the pitch.

Implementations

Based upon the results of this study, the following implementations are recommended for teachers, coaches and pitchers who are involved with fast and change-up windmill pitching in softball:

1. Stride length should not vary significantly for the fast and change-up pitches within a given pitcher. The recommended stride length range is 80 to 90 percent of subjects' height.

2. The vertical ground reaction force of the pivot foot may not significantly contribute to ball velocity. The greater attention should be placed on the study of the stride foot.

3. From the highest point of the backswing motion, the arm must be accelerated as forcefully and rapidly as possible. For this reason, the pitcher must have strong shoulder flexors (pectoralis major, teres major, latissimus dorsi) and adductors.

4. Rapid deceleration, or slowing down of the arm prior to release of the ball is another important movement which occurs during the pitching motion. This is a critical movement, and the pitcher must have very strong

shoulder extensors (posterior deltoid, rotator cuff muscles) to execute this effectively.

5. Pitchers need to work on specific strengthening exercises especially of the shoulder to execute these rotation movements efficiently and also to prevent injuries.

Recommendations

The results of this study prompted the investigator to make the following recommendations:

1. That a further study be conducted to examine more closely the rotations that occur in each arm segment and the hip during the pitch.

2. That more detailed ground reaction force data be collected on the instant of stride foot contact with force platform before the release of the ball

3. That a three-dimensional study concentrating on the arm action associated with pitching fast balls be done using cameras with speeds greater than 120 frames per second.

4. That the EMG analysis of muscular activities be done on the muscle group related to the shoulder of the pitching arm to obtain a more comprehensive understanding of windmill style pitching, coupled with three-dimensional analysis.

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APPENDICES

APPENDIX A

HUMAN SUBJECT APPROVAL AND INFORMED CONSENT FORM

**MICHIGAN STATE
UNIVERSITY**

March 29, 1995

TO: Sang Y. Woo
6127 Farrington Ct. #11
E. Lansing, MI 48823

RE: IRB#: 95-138
TITLE: A THREE-DIMENSIONAL ANALYSIS OF THE WINDMILL
STYLE OF SOFTBALL DELIVERY FOR FAST AND CURVE
BALL PITCHING
REVISION REQUESTED: N/A
CATEGORY: 2-G
APPROVAL DATE: 03/29/95

The University Committee on Research Involving Human Subjects' (UCRIHS) review of this project is complete. I am pleased to advise that the rights and welfare of the human subjects appear to be adequately protected and methods to obtain informed consent are appropriate. Therefore, the UCRIHS approved this project including any revision listed above.

RENEWAL: UCRIHS approval is valid for one calendar year, beginning with the approval date shown above. Investigators planning to continue a project beyond one year must use the green renewal form (enclosed with the original approval letter or when a project is renewed) to seek updated certification. There is a maximum of four such expedited renewals possible. Investigators wishing to continue a project beyond that time need to submit it again for complete review.

REVISIONS: UCRIHS must review any changes in procedures involving human subjects, prior to initiation of the change. If this is done at the time of renewal, please use the green renewal form. To revise an approved protocol at any other time during the year, send your written request to the UCRIHS Chair, requesting revised approval and referencing the project's IRB # and title. Include in your request a description of the change and any revised instruments, consent forms or advertisements that are applicable.



OFFICE OF
**RESEARCH
AND
GRADUATE
STUDIES**

**PROBLEMS/
CHANGES:**

Should either of the following arise during the course of the work, investigators must notify UCRIHS promptly: (1) problems (unexpected side effects, complaints, etc.) involving human subjects or (2) changes in the research environment or new information indicating greater risk to the human subjects than existed when the protocol was previously reviewed and approved.

If we can be of any future help, please do not hesitate to contact us at (517)355-2180 or FAX (517)336-1171.

University Committee on
Research Involving
Human Subjects
(UCRIHS)

Michigan State University
232 Administration Building
East Lansing, Michigan
48824-1046

517/355-2180
FAX: 517/432-1171

Sincerely,

David E. Wright
David E. Wright, Ph.D.
UCRIHS Chair

DEW:pja

cc: Eugene W. Brown

INFORMED WRITTEN CONSENT FORM

I am a graduate student at Michigan State University. This investigation is part of a doctoral dissertation being conducted in order to analyze the softball windmill pitching motion. Two high speed video cameras and a force platform will be used to collect data from the pitching motion. Additionally, anthropometric (e.g., height, weight, body segment length, and girth) measurements will be taken by a skilled researcher familiar with these procedures.

In order for all measurements to be collected, a subject will participate for approximately one hour. The procedures will be explained to each athlete and every effort will be made to make each participant comfortable. The choice to participate in this study is completely voluntary. Prior to the filming, the subjects will be allowed adequate time to warm up properly and then asked to perform three trials of each pitch (fast ball and curve ball).

The data collected will be kept in strict confidence with no one knowing the identify of the participants other than the principal investigator (Mr. Sang Yeon Woo, Doctoral Candidate, Michigan State University). Film and force platform records will only be used for data collection and presentations associated with this study. The identity of each participant will not be revealed. Any part of the participant's data may be requested by the participants or their parents/guardians and will be made available as soon as possible. At any time, a participant is free to drop out of this study or to seek additional information. No beneficial results are guaranteed from participation in this study. A signed written consent form from the athlete and/or her parent/guardian will be required for participation in this study.

I, _____ have read the above statement and agree to participate as a subject in this study under the conditions stated above.

Signature of participant

Date

Signature of parent/guardian

Date

Investigator: Sang Yeon Woo (Phone: 517-336-9566)

Dear Parents (Guardian) and Softball Pitchers:

I am a graduate student at Michigan State University. This investigation is being conducted in order to analyze the windmill softball pitching motion. Two high speed video cameras and a force platform will be used to collect the data. Additionally, anthropometric (e.g., height, weight, body segment length, and girth) measurements will be taken by a skilled researcher familiar with these procedures.

I am seeking several highly skilled softball pitchers to participate in a study of the windmill style of delivery. Those selected for participation will be invited to the Michigan State University campus. Approximately one hour will be required to complete all measurements. These procedures will be explained to the participants and every effort will be made to make the athletes comfortable. The participant's choice to become involved in this study is completely voluntary.

The data collected will be kept in strict confidence with no one knowing the identify of the participant other than the principal investigator (Mr. Sang Yeon Woo, Doctoral Candidate, Michigan State University). Film and force platform records will only be used for data collection and presentations associated with this study. The participant's identity will not be revealed. Any part of the data may be requested by the parent/guardian or participant and will be made available as soon as possible. No beneficial results are guaranteed as a result of participation in this study. A signed consent form will be required before anyone is permitted to participate.

If you have any questions or concerns about this study, please feel free to contact the investigator at any time.

Thank you for your consideration of the study.

Sincerely,

Sang Yeon Woo, Doctoral Candidate
Department of Physical Education and Exercise Science
Michigan State University
(517) 336-9566 (Home)

QUESTIONNAIRE

Name: _____ Date of Birth: _____

Address: _____
(Street) (City) (State) (Zip)

Telephone: _____

Name of softball team: _____

Current pitching record: _____

Current earned run average: _____

Are you a right-handed or left-handed pitcher? _____

Are you a windmill or a slingshot pitcher? _____

How long have you been involved in softball pitching? _____ *(seasons)

Relative to other softball pitchers my age, I believe that I have a(n) _____ fast ball.

a) excellent b) good c) average d) less than average e) poor

[Circle one response.]

Relative to other softball pitchers my age, I believe that I have a(n) _____ curve ball.

a) excellent b) good c) average d) less than average e) poor

[Circle one response.]

Is your current pitching motion adversely effected by current or past injuries?

Yes _____ No _____ [Check one response.]

ANTHROPOMETRIC MEASURES

Subject's Name: _____ Birth of Date: _____

Address: _____
(Street) (City) (State) (Zip)

Subject Number: _____ Telephone: _____

_____ Weight (1/4 lb.)

_____ Biacromial breadth

_____ Biilac breadth

_____ Bitrochanteric breadth

_____ Brachium length (acromradiale)

_____ Forearm length (radiostylion)

_____ Humerus width (biepicondylar)

_____ Wrist width (radionular)

_____ Femur width (bicondylar)

_____ Hand length

_____ Thigh-plus-leg length

_____ Standing height

_____ Sitting height

_____ Biceps girth (elbow ext.)

_____ Forearm girth

Anthropometric Measures

ID ¹	Bc ²	Bl ³	Bt ⁴	Br ⁵	Fa ⁶	Hm ⁷	Wr ⁸	Fm ⁹	Ha ^A	Tl ^B	Sh ^C	Bc ^D	Fg ^E
M1	35.3	23.6	27.2	31.2	23.8	3.7	2.9	6.3	14.7	79.8	81.6	25.4	22.8
M2	36.2	26.6	28.5	31.6	24.4	5.8	5.5	8.7	18.4	77.3	85.9	22.6	23.4
M3	32.4	23.8	25.3	28.5	23.0	5.9	5.2	8.4	16.5	74.2	78.6	21.2	22.0
M4	36.1	29.5	29.5	30.9	26.1	5.3	5.4	9.0	17.6	75.7	82.8	26.5	22.9
M5	36.6	28.4	30.3	31.3	23.9	5.4	5.2	9.2	17.3	85.4	84.2	26.5	23.6
M6	34.1	23.2	26.8	29.8	24.0	5.6	5.4	8.6	16.4	82.1	81.0	21.9	21.9
H1	35.0	27.6	30.8	29.1	23.4	7.2	5.6	10.7	16.7	68.1	84.2	27.9	25.5
H2	34.6	26.1	26.2	28.0	24.6	4.9	6.1	9.1	17.2	73.0	85.1	23.5	21.5
H3	38.4	31.0	34.1	31.0	26.1	6.4	5.5	9.8	17.7	87.6	90.6	31.4	24.8
H4	35.3	31.4	31.1	30.1	24.2	6.8	5.2	9.3	17.7	85.6	86.7	22.8	22.5
H5	33.9	25.1	27.2	28.3	22.9	5.4	4.9	8.1	16.0	71.0	83.3	22.3	22.0
H6	35.5	25.6	31.2	30.1	24.6	5.9	5.3	9.0	16.2	78.8	84.6	22.5	22.3
C1	38.1	29.4	32.4	25.1	24.9	8.4	5.2	5.7	14.7	80.4	86.9	26.4	22.8
C2	37.3	25.5	27.7	24.3	22.4	5.7	4.9	8.5	12.9	75.1	84.6	24.5	21.9
C3	37.1	27.7	30.6	25.6	23.9	6.8	5.1	9.6	14.6	76.1	84.2	24.6	22.5
C4	37.3	26.9	29.3	25.1	22.5	6.2	5.0	9.0	14.6	75.9	87.6	25.8	25.4
C5	35.9	27.3	29.2	24.1	22.1	5.6	4.9	8.5	13.1	74.6	85.9	25.2	23.6
C6	38.5	34.2	36.9	27.5	26.1	6.6	5.3	9.7	15.8	72.1	94.0	32.1	27.2

¹ M: Middle School H: High School C: College

² Biacromial breadth(cm), ³ Biilac breadth(cm),

⁴ Bitrochanteric breadth (cm), ⁵ Brachium length(cm), ⁶ Forearm length(cm),

⁷ Humerus width(cm), ⁸ Wrist width(cm), ⁹ Femur width(cm), ^A Hand length(cm),

^B Thigh-plus-leg length(cm), ^C Sitting height(cm), ^D Biceps girth(cm),

^E Forearm girth(cm)

APPENDIX B
DATA TABLE OF RESULTS

1.a Characteristics of Middle School Subjects

Subject	Height (cm)	Mass (kg)	Age (yrs)
1	160.9	54.3	15
2	162.7	54.3	14
3	151.4	40.7	13
4	157.7	53.1	13
5	161.5	56.7	14
6	155.6	42.7	12
Mean	158.3	50.3	13.5
S.D.	4.3	6.8	1.1

1.b Characteristics of High School Subjects

Subject	Height (cm)	Mass (kg)	Age (yrs)
1	154.6	66.1	15
2	160.1	45.0	16
3	168.5	80.6	16
4	161.4	54.4	17
5	153.6	48.3	15
6	162.6	51.0	17
7	165.6	53.3	15
Mean	160.9	57.0	15.9
S.D.	5.4	12.4	0.9

1.c Characteristics of College Subjects

Subject	Height (cm)	Mass (kg)	Age (yrs)
1	168.1	64.5	26
2	164.7	52.5	18
3	167.6	59.7	17
4	164.1	57.3	19
5	163.8	53.9	30
6	174.9	86.9	17
Mean	167.2	62.5	21.2
S.D.	4.2	12.7	5.5

2.a Temporal Analysis of Middle School Subjects

Subject	Fast (s)				Change-Up (s)			
	A	B	C	D	A	B	C	D
1	.510	.170	.204	0	.544	.170	.204	0
2	.612	.136	.102	0	.646	.204	.102	0
3	.510	.170	.136	0	.527	.187	.153	0
4	.527	.187	.153	0	.544	.204	.170	0
5	.544	.204	.136	0	.544	.238	.136	0
6	.527	.153	.119	0	.527	.187	.119	0
Mean	.538	.170	.142	0	.555	.198	.147	0
S.D	.038	.024	.035	0	.045	.023	.037	0

2.b Temporal Analysis of High School Subjects

Subject	Fast (s)				Change-Up (s)			
	A	B	C	D	A	B	C	D
1	.510	.170	.102	0	.544	.170	.068	0
2	.476	.136	.102	0	.578	.204	.136	0
3	.544	.170	.136	0	.578	.204	.170	0
4	.510	.136	.102	0	.544	.170	.136	0
5	.510	.136	.102	0	.544	.170	.136	0
6	.544	.170	.102	0	.578	.204	.102	0
Mean	.513	.155	.112	0	.559	.184	.126	0
S.D	.023	.018	.017	0	.018	.018	.032	0

2.c Temporal Analysis of College Subjects

Subject	Fast (s)				Change-Up (s)			
	A	B	C	D	A	B	C	D
1	.510	.170	.102	0	.510	.170	.102	0
2	.561	.153	.119	0	.544	.170	.102	0
3	.544	.170	.136	0	.544	.204	.170	0
4	.527	.136	.119	0	.561	.187	.170	0
5	.595	.170	.136	0	.680	.204	.170	0
6	.595	.170	.119	0	.578	.170	.136	0
Mean	.555	.162	.122	0	.570	.184	.142	0
S.D	.035	.014	.013	0	.057	.017	.033	0

2.d ANOVA for Interval A

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	.04	15	.00	
AGE	.00	2	.00	.68
WITHIN+RESIDUAL	.01	15	.00	
INTERVAL A	.01	1	.01	13.75**
AGE BY INTERVAL A	.00	2	.00	2.09

** P < .01

2.e ANOVA for Interval B

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	.01	15	.00	
AGE	.00	2	.00	1.28
WITHIN+RESIDUAL	.00	15	.0	
INTERVAL B	.01	1	.01	30.41**
AGE BY INTERVAL B	.00	2	.00	.41

** P < .01

2.f ANOVA for Interval C

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	.02	15	.00	
AGE	.00	2	.00	1.60
WITHIN+RESIDUAL	.00	15	.00	
INTERVAL C	.00	1	.00	7.17*
AGE BY INTERVAL C	.00	2	.00	.67

* P < .05

3.a Ball Velocity of Windmill Pitches for Middle School
Subjects

Subject	Fast (m/s)	Change-Up (m/s)	Difference (m/s)
1	19.49	17.18	2.31
2	23.35	20.20	3.15
3	18.96	18.17	0.79
4	18.54	17.29	1.25
5	22.31	18.73	3.58
6	24.65	18.46	6.19
Mean	21.22	18.34	2.88
S.D	2.56	1.11	1.94

3.b Ball Velocity of Windmill Pitches for High School
Subjects

Subject	Fast (m/s)	Change-Up (m/s)	Difference (m/s)
1	21.66	15.76	5.90
2	20.38	15.44	4.94
3	23.31	15.57	7.74
4	19.71	17.83	1.88
5	24.62	18.44	6.18
6	25.74	19.11	6.63
Mean	22.57	17.03	5.55
S.D	2.39	1.63	2.01

3.c Ball Velocity of Windmill Pitches for College Subjects

Subject	Fast (m/s)	Change-Up (m/s)	Difference (m/s)
1	25.68	19.52	6.16
2	21.21	17.83	3.38
3	23.48	19.69	3.79
4	25.94	16.63	9.31
5	21.39	16.88	4.51
6	22.62	20.19	2.43
Mean	23.39	18.46	4.93
S.D	2.05	1.54	2.48

3.d ANOVA for Ball Velocity

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	78.67	15	5.24	
AGE	10.29	2	5.15	.98
WITHIN+RESIDUAL	35.01	15	2.33	
BALL VELOCITY	178.31	1	178.31	76.40**
AGE BY BALL VELOCITY	11.70	2	5.85	2.51

** P < .01

4.a Stride Length of Middle School Subjects

Subject	Fast (%)	Ranks	Change-Up (%)	Ranks
1	78.9	2	77.8	2
2	87.5	5	92.1	5
3	84.4	4	81.3	4
4	75.0	1	78.5	3
5	84.0	3	75.5	1
6	90.2	6	95.9	6
Mean	83.3		83.5	
S.D	5.6		8.4	

4.b Stride Length of High School Subjects

Subject	Fast (%)	Ranks	Change-Up (%)	Ranks
1	92.7	5	93.1	4
2	82.9	2	72.3	1
3	81.0	1	79.1	2
4	113.3	6	106.1	6
5	89.4	4	94.1	5
6	84.4	3	90.3	3
Mean	90.6		89.2	
S.D	11.9		11.9	

4.c Stride Length of College Subjects

Subject	Fast(%)	Ranks	Change-Up(%)	Ranks
1	80.2	3	78.2	3
2	113.7	5	114.1	5
3	104.5	4	102.9	4
4	120.9	6	118.0	6
5	76.3	2	70.6	2
6	76.2	1	77.1	1
Mean	95.3		93.5	
S.D	20.2		20.7	

4.d ANOVA for Stride Length

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	5911.91	15	394.13	
AGE	729.34	2	364.67	.93
WITHIN+RESIDUAL	194.83	15	12.99	
STRIDE LENGTH	9.51	1	9.51	.73
AGE BY STRIDE LENGTH	6.80	2	3.40	.26

5.a Contributions to the Fast Ball Velocity at Release for Middle School Subjects.

Subject	Fast (cm/s)					
	C1	C2	C3	C4	C5	C6
1	433.99	808.56	154.09	267.40	205.81	217.19
2	367.44	611.73	237.32	288.95	230.60	182.20
3	279.95	567.29	52.65	210.60	164.53	179.32
4	242.98	524.48	28.70	201.94	200.00	168.28
5	337.32	545.85	95.58	245.26	268.75	213.03
6	316.55	659.60	283.06	229.02	183.96	185.30
Mean	329.71	619.59	141.90	240.53	208.94	190.89
	(19.0%)	(35.8)	(8.2%)	(13.9%)	(8.28%)	(9.07%)
S.D	67.12	104.49	102.08	33.49	36.69	19.67

5.b Contributions to the Change-up Ball Velocity at Release for Middle School Subjects.

Subject	Change-up (cm/s)					
	C1	C2	C3	C4	C5	C6
1	357.42	676.94	124.13	260.85	219.81	202.12
2	393.52	645.31	253.39	291.10	265.10	201.84
3	277.74	544.44	54.24	208.16	206.23	186.87
4	236.90	537.27	52.65	185.38	202.51	174.04
5	276.69	474.62	150.93	199.77	234.57	180.93
6	422.87	725.31	127.67	292.81	205.66	247.62
Mean	327.45	600.65	127.17	239.68	222.32	198.90
	(19.1%)	(35.0%)	(7.4%)	(14.0)	(19.9%)	(11.59%)
S.D	74.39	96.35	74.00	47.85	24.14	26.38

5.c Contributions to the Fast Ball Velocity at Release for High School Subjects.

Subject	Fast (cm/s)					
	C1	C2	C3	C4	C5	C6
1	317.93	599.58	89.89	231.07	205.55	221.97
2	384.19	678.38	-16.15	263.76	241.40	217.68
3	437.58	710.11	-22.10	287.93	203.81	200.21
4	358.46	613.85	52.75	294.99	269.64	282.72
5	382.58	737.67	286.73	293.93	235.83	226.70
6	383.15	738.14	56.19	249.29	180.03	221.14
Mean	377.32	679.62	74.55	279.16	222.71	228.41
	(20.3%)	(36.5%)	(4.0%)	(15.0%)	(12.0%)	(12.3%)
S.D	39.05	60.76	112.81	26.46	32.24	28.15

5.d. Contributions to the Change-up Ball Velocity at Release for High School Subjects.

Subject	Change-up (cm/s)					
	C1	C2	C3	C4	C5	C6
1	346.66	627.50	52.70	241.66	272.74	235.13
2	287.69	627.28	110.05	214.54	155.07	176.57
3	488.17	723.82	73.29	243.65	198.07	192.80
4	335.74	580.15	159.06	256.57	232.58	239.78
5	396.78	791.24	54.60	262.58	155.13	249.58
6	378.86	658.69	202.05	260.72	218.29	234.38
Mean	372.32	668.11	108.63	246.62	205.31	221.37
	(20.4%)	(36.7%)	(6.0%)	(13.5%)	(11.3%)	(12.2%)
S.D	68.15	76.69	60.94	17.73	45.94	29.38

5.e Contributions to the Fast Ball Velocity at Release for College Subjects.

Subject	Fast (cm/s)					
	C1	C2	C3	C4	C5	C6
2	347.23	583.76	333.18	251.26	288.89	283.96
3	391.18	637.49	255.64	318.52	263.41	281.58
4	368.73	611.33	-23.91	311.45	185.81	229.86
5	366.72	653.66	24.88	293.32	273.58	187.68
6	294.58	554.00	156.79	215.45	221.15	193.05
Mean	353.69	608.05	149.32	278.00	246.59	235.23
	(18.9%)	(32.5%)	(8.0%)	(14.9%)	(13.2%)	(12.6%)
S.D	36.53	40.22	150.55	43.65	42.24	46.35

5.f Contributions to the Change-up Ball Velocity at Release for College Subjects.

Subject	Change-up (cm/s)					
	C1	C2	C3	C4	C5	C6
2	399.37	637.31	362.53	267.90	281.30	285.27
3	378.86	657.73	333.79	315.14	225.04	269.35
4	404.17	757.87	132.49	289.46	156.13	231.33
5	325.69	564.63	131.53	251.96	209.59	172.57
6	329.33	552.58	133.44	216.58	188.22	187.18
Mean	367.48	634.02	218.74	268.21	212.10	229.14
	(19.0%)	(32.9%)	(11.3%)	(7.2%)	(11.0%)	(11.9%)
S.D	37.73	87.70	14.79	37.36	46.54	49.33

6.a. Angular Displacement of the Arm (JD3) for Middle School Subjects

Subject	Fast (Deg.)		Change-Up (Deg.)	
	Highest Pt.	Release	Highest Pt.	Release
	JD3	JD3	JD3	JD3
1	442.6	627.1	463.5	622.4
2	497.4	616.4	414.8	636.0
3	476.0	629.6	460.3	626.9
4	486.1	630.7	473.9	630.3
5	470.9	621.2	453.3	621.3
6	489.1	626.1	509.2	635.6
Mean	477.0	625.2	462.5	628.8
S.D	19.3	5.4	30.6	6.3

6.b Angular Displacement of the Arm (JD3) for High School Subjects

Subject	Fast (Deg.)		Change-Up (Deg.)	
	Highest Pt.	Release	Highest Pt.	Release
	JD3	JD3	JD3	JD3
1	425.5	639.8	483.7	628.1
2	469.5	621.7	449.7	633.1
3	450.2	618.9	459.3	636.6
4	493.7	626.0	462.0	621.8
5	521.6	621.7	486.5	641.6
6	461.6	626.1	460.7	625.5
Mean	470.4	625.7	467.0	631.1
S.D	33.7	7.4	14.7	7.4

6.c Angular Displacement of the Arm (JD3) for College Subjects

Subject	Fast (Deg.)		Change-Up (Deg.)	
	Highest Pt.	Release	Highest Pt.	Release
	JD3	JD3	JD3	JD3
2	466.4	626.2	474.0	626.7
3	482.0	607.9	457.8	608.2
4	477.0	620.6	445.8	624.0
5	488.9	625.9	480.9	625.8
6	491.6	626.4	484.3	626.8
Mean	481.2	621.4	468.9	622.7
S.D	10.1	7.9	16.3	7.2

6.d ANOVA for Angular Displacement of the Arm (JD3)

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	775.11	14	55.37	
AGE	253.01	2	126.50	2.28
WITHIN+RESIDUAL	626.88	14	44.78	
ARM (JD3)	91.58	1	91.58	2.05
AGE BY ARM (JD3)	27.90	2	13.95	.31

7.a Flexion-Extension Angles at the Elbow Joint at Release
for Middle School Subjects

Subject	Fast (Deg.)	Change-Up (Deg.)
1	163.86	155.97
2	135.34	147.69
3	142.91	141.13
4	131.74	147.35
5	130.95	129.68
6	137.17	153.08
Mean	140.33	145.82
S.D	12.30	9.42

7.b Flexion-Extension Angles at the Elbow Joint at Release
for High School Subjects

Subject	Fast (Deg.)	Change-Up (Deg.)
1	136.61	157.57
2	155.39	164.40
3	156.54	162.02
4	155.54	151.06
5	116.32	148.11
6	151.22	155.92
Mean	146.27	156.51
S.D	16.64	6.23

7.c Flexion-Extension Angles at the Elbow Joint at Release
for College Subjects

Subject	Fast (Deg.)	Change-Up (Deg.)
2	144.05	162.41
3	138.69	147.46
4	136.85	143.28
5	150.16	151.53
6	144.92	137.05
Mean	142.93	148.35
S.D	5.30	9.51

7.d ANOVA for Flexion-Extension Angles at the Elbow Joint

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	2276.62	14	162.62	
AGE	379.55	2	189.78	1.17
WITHIN+RESIDUAL	876.58	14	62.61	
ELBOW FLEXION	459.70	1	459.70	7.34*
AGE BY ELBOW FLEXION	65.08	2	32.54	.52

* $P < .05$

8.a Peak Angular Velocity of the JA3 and JA4 for Middle School Subjects

Subject	Shoulder(deg/s)		Elbow(deg/s)	
	Fast	Change-up	Fast	Change-up
1	1031.9	847.1	1203.5	1191.9
2	1281.8	1160.0	1340.2	1245.0
3	1077.1	1115.7	1437.2	1505.0
4	945.7	908.9	1564.1	1257.1
5	860.2	859.2	1519.7	1257.5
6	1188.4	1105.5	1518.8	1117.6
Mean	1064.2	999.4	1430.6	1262.7
S.D	154.7	142.6	136.6	130.5

8.b Peak Angular Velocity of the JA3 and JA4 for High School Subjects

Subject	Shoulder(deg/s)		Elbow(deg/s)	
	Fast	Change-up	Fast	Change-up
1	1236.3	1055.1	1530.1	1459.0
2	1515.2	1142.1	1768.9	1240.0
3	1358.0	1110.6	1367.8	1057.0
4	1366.3	1240.0	1345.1	1208.8
5	1456.3	1114.9	1596.3	1336.5
6	1286.2	1058.2	1347.0	1126.7
Mean	1369.7	1120.2	1492.5	1238.0
S.D	104.2	67.9	171.5	144.6

8.c Peak Angular Velocity of the JA3 and JA4 for College Subjects

Subject	Shoulder(deg/s)		Elbow(deg/s)	
	Fast	Change-up	Fast	Change-up
2	1267.8	1140.0	1408.2	1257.9
3	972.4	984.4	1467.6	1281.6
4	1435.4	1219.3	1665.8	1679.4
5	966.9	835.9	1518.5	1206.4
6	1120.4	1197.0	1337.4	1314.3
Mean	1152.6	1075.3	1479.5	1347.9
S.D	200.8	162.3	124.1	189.4

8.d ANOVA for JA3

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	497471.54	14	35533.68	
AGE	276783.07	2	138391.53	3.89
WITHIN+RESIDUAL	66957.01	14	4782.64	
PEAK VELOCITY	143773.49	1	143773.49	30.06**
AGE BY PEAK VELOCITY	62487.45	2	31243.73	6.53

** P < .01

8.e ANOVA for JA4

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	453267.13	14	32376.22	
AGE	25738.41	2	12869.21	.40
WITHIN+RESIDUAL	181976.58	14	12998.33	
PEAK VELOCITY	288093.96	1	288093.96	22.16**
AGE BY PEAK VELOCITY	22410.19	2	11205.10	.86

** P < .01

9.a Average Force of the Shoulder Joint during the
Execution Phase in Middle School Subjects

Subject	Fast (N)			Change-Up (N)		
	JF1	JF2	JF3	JF1	JF2	JF3
1	162.80	69.04	24.85	118.22	34.53	19.68
2	145.13	126.69	31.15	111.06	30.56	20.15
3	95.15	59.52	6.70	86.58	46.68	4.55
4	84.61	93.00	2.64	87.10	79.28	4.84
5	95.38	66.12	17.64	75.15	55.83	21.47
6	101.62	103.68	37.62	107.19	41.58	17.86
Mean	114.12	86.34	20.10	97.55	48.08	14.76
S.D	31.84	26.08	13.73	16.94	17.71	7.88

9.b Average Force of the Shoulder Joint during the
Execution Phase in High School Subjects

Subject	Fast (N)			Change-Up (N)		
	JF1	JF2	JF3	JF1	JF2	JF3
1	134.64	90.42	49.27	150.68	-0.65	32.48
2	177.15	-10.97	18.36	100.98	38.99	5.85
3	249.46	28.37	-4.67	205.11	83.47	5.24
4	118.31	99.10	7.62	95.46	68.79	21.69
5	114.52	121.49	58.46	138.38	62.69	-5.53
6	141.85	92.66	18.56	111.09	41.02	31.96
Mean	155.99	70.22	24.60	133.62	49.05	15.28
S.D	50.95	50.46	24.39	41.12	29.65	15.73

9.c Average Force of the Shoulder Joint during the
Execution Phase in College Subjects

Subject	Fast (N)			Change-Up (N)		
	JF1	JF2	JF3	JF1	JF2	JF3
2	146.77	-2.18	33.80	109.78	26.69	49.55
3	112.96	47.92	67.21	97.21	37.80	49.88
4	155.58	157.89	5.07	142.52	33.94	17.91
5	127.98	29.40	8.94	93.07	36.10	16.56
6	220.41	101.72	35.56	217.09	125.61	49.53
Mean	152.74	66.95	30.12	131.93	52.03	36.71
S.D	41.28	63.30	24.97	51.41	41.35	17.78

9.d ANOVA for JF1

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	40358.61	14	2882.76	
AGE	11156.65	2	5578.32	1.94
WITHIN+RESIDUAL	4967.28	14	354.81	
FORCE	3346.11	1	3346.11	9.43**
AGE BY FORCE	53.73	2	26.87	.08

** P < .01

10.a Average Force of the Elbow Joint during the Execution Phase in Middle School Subjects

Subject	Fast (N)			Change-Up (N)		
	JF4	JF5	JF6	JF4	JF5	JF6
1	111.92	42.03	9.97	83.97	19.70	5.98
2	105.20	83.10	21.77	75.00	12.23	11.06
3	68.82	35.37	2.45	61.52	27.15	2.30
4	62.81	57.63	3.45	65.19	46.26	4.11
5	65.76	37.83	7.14	51.67	30.78	11.34
6	76.36	61.95	24.25	73.43	24.88	8.83
Mean	81.81	52.99	11.51	68.48	26.83	7.27
S.D	21.31	18.27	9.34	11.39	11.50	3.73

10.b Average Force of the Elbow Joint during the Execution Phase in High School Subjects

Subject	Fast (N)			Change-Up (N)		
	JF4	JF5	JF6	JF4	JF5	JF6
1	96.19	53.01	25.54	109.35	-3.73	12.74
2	128.05	-12.94	0.16	68.62	18.88	2.29
3	173.16	12.42	-12.64	135.97	40.75	-4.67
4	88.91	67.13	-2.69	69.43	40.63	9.49
5	85.58	84.89	40.98	101.52	37.64	-5.98
6	97.25	56.02	7.73	75.99	22.34	18.82
Mean	111.52	43.42	9.85	93.48	26.09	5.45
S.D	33.75	36.52	19.88	26.92	17.41	9.91

10.c Average Force of the Elbow Joint during the Execution Phase in College Subjects

Subject	Fast (N)			Change-Up (N)		
	JF4	JF5	JF6	JF4	JF5	JF6
2	105.21	-9.53	9.54	77.91	11.09	20.25
3	84.45	27.08	35.50	69.70	18.74	27.22
4	117.59	98.98	-2.74	98.97	15.81	5.69
5	92.93	14.70	4.01	64.28	18.58	10.42
6	160.41	56.69	16.68	156.28	77.10	22.46
Mean	112.12	37.58	12.60	93.43	28.26	17.21
S.D	29.76	41.80	14.69	37.53	27.47	8.89

10.d ANOVA for JF4

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	18661.49	14	1332.96	
AGE	5867.12	2	2933.56	2.20
WITHIN+RESIDUAL	2755.74	14	196.84	
FORCE	2351.41	1	2351.41	11.95*
AGE BY FORCE	48.89	2	24.44	.12

** P < .01

11.a Average Torque of the Shoulder Joint during Execution Phase in Middle School Subjects

Subject	Fast (Nm)			Change-Up (Nm)		
	JT1	JT2	JT3	JT1	JT2	JT3
1	0.53	14.63	2.69	0.12	9.85	3.52
2	-3.13	5.74	-10.28	1.20	2.41	-6.02
3	3.47	2.48	-3.61	5.11	0.98	-2.91
4	5.25	2.21	-5.41	4.97	1.35	-2.19
5	7.53	0.98	-7.85	5.13	0.62	-8.11
6	2.46	6.15	-8.63	2.63	0.61	0.50
Mean	2.48	5.37	-5.52	3.15	2.64	-2.54
S.D	3.87	4.98	4.67	2.27	3.60	4.23

11.b Average Torque of the Shoulder Joint during Execution Phase in High School Subjects

Subject	Fast (Nm)			Change-Up (Nm)		
	JT1	JT2	JT3	JT1	JT2	JT3
1	5.89	9.98	-8.44	2.18	3.63	7.68
2	4.52	3.45	-3.73	0.40	1.81	-2.72
3	10.29	-0.88	-6.35	9.03	-0.18	-6.41
4	-3.72	7.74	-5.81	-1.14	2.59	-5.19
5	-3.92	13.53	-6.03	2.22	9.56	1.87
6	5.98	6.23	-6.25	2.76	3.91	-4.15
Mean	3.17	6.68	-6.10	2.58	3.55	-3.32
S.D	5.57	5.03	1.50	3.48	3.29	3.20

11.c Average Torque of the Shoulder Joint
during Execution Phase in College Subjects

Subject	Fast (Nm)			Change-Up (Nm)		
	JT1	JT2	JT3	JT1	JT2	JT3
2	-6.00	5.37	-3.58	-3.09	4.95	-3.28
3	4.03	14.75	-8.89	2.57	10.25	-7.10
4	11.17	6.98	-9.00	6.74	3.44	-1.02
5	4.16	5.18	1.71	1.13	5.72	-2.67
6	-1.42	14.05	-17.20	4.00	10.93	-13.18
Mean	2.48	9.27	-7.39	2.27	7.06	-5.45
S.D	6.51	4.75	7.04	3.64	3.34	4.86

11.d ANOVA for JT3

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	472.46	14	33.75	
AGE	44.84	2	22.42	.66
WITHIN+RESIDUAL	171.80	14	12.27	
TORQUE	85.27	1	85.27	6.95*
AGE BY TORQUE	10.09	2	5.04	.41

* $P < .05$

12.a Average Torque of the Elbow Joint during Execution
Phase in Middle School Subjects

Subject	Fast (Nm)			Change-Up (Nm)		
	JT4	JT5	JT6	JT4	JT5	JT6
1	-0.76	6.30	-1.13	-1.81	5.37	0.66
2	-1.08	2.21	-0.29	-0.75	2.08	-0.72
3	-1.01	1.68	-1.07	0.04	1.34	-0.76
4	0.27	1.59	1.21	0.58	1.02	1.16
5	0.92	2.17	-2.59	-0.81	0.63	-2.44
6	1.64	4.09	-1.97	-0.93	0.73	0.12
Mean	0.00	3.01	-0.97	-0.61	1.86	-0.50
S.D	1.13	1.85	1.14	0.83	1.80	1.40

12.b Average Torque of the Elbow Joint during Execution
Phase in High School Subjects

Subject	Fast (Nm)			Change-Up (Nm)		
	JT4	JT5	JT6	JT4	JT5	JT6
1	1.79	7.51	-3.05	-0.28	6.15	1.05
2	-1.24	1.11	-3.47	-2.68	0.93	-3.28
3	2.66	1.20	-0.60	-2.04	-0.66	-4.97
4	-0.43	2.45	-1.64	-1.80	1.36	-2.16
5	-0.45	8.37	-0.37	-1.21	5.82	2.93
6	1.95	3.34	-3.26	0.41	2.73	-1.04
Mean	0.71	4.00	-2.07	-1.27	2.72	-1.25
S.D	1.61	3.18	1.38	1.16	2.75	2.88

12.c. Average Torque of the Elbow Joint during Execution
Phase in College Subjects

Subject	Fast (Nm)			Change-Up (Nm)		
	JT4	JT5	JT6	JT4	JT5	JT6
2	-4.65	2.19	-4.23	-1.48	1.58	-1.94
3	1.63	6.07	-6.23	-0.47	3.67	-3.55
4	0.74	7.37	-6.44	0.49	3.82	-1.07
5	0.62	2.85	-0.96	-0.77	1.94	-1.73
6	-2.10	7.29	-8.79	-0.39	5.26	-6.86
Mean	-0.75	5.10	-5.33	-0.52	3.25	-3.03
S.D	2.59	2.56	2.93	0.71	1.50	2.33

12.d ANOVA for JT6

Source of Variation	SS	DF	MS	F
WITHIN+RESIDUAL	87.95	14	6.28	
AGE	70.70	2	35.35	5.63*
WITHIN+RESIDUAL	36.26	14	2.59	
TORQUE	13.28	1	13.28	5.13*
AGE BY TORQUE	4.39	2	2.19	.85

* P < .05

13.a Ground Reaction Analysis of Middle School Subjects

Subject	Fast				Change-Up			
	a	b	c	d	a	b	c	d
2	814.08	1.484	1.644	1.581	784.45	1.594	2.022	2.023
3	480.35	0.976	1.165	1.122	448.23	0.757	0.906	0.918
4	723.31	1.364	1.484	1.153	713.54	1.304	1.424	1.428
5	1098.93	1.265	1.404	1.377	895.07	1.146	1.285	1.275
6	566.92	1.743	2.211	2.210	533.41	2.071	2.480	2.380
Mean	736.72	1.366	1.581	1.561	675.00	1.374	1.623	1.605
S.D	240.79	0.282	0.394	0.403	182.64	0.493	0.626	0.589

a: the maximum Z ground reaction force

b: the time of reaching the maximum Z ground reaction force

c: the time of takeoff on pivot foot from the force platform

d: the time of ball release

13.b Ground Reaction Analysis of High School Subjects

Subject	Fast				Change-Up			
	a	b	c	d	a	b	c	d
1	703.76	1.462	1.837	2.227	703.76	1.972	2.480	2.431
2	684.21	2.261	2.679	2.618	646.51	1.932	2.440	2.414
3	1030.51	1.525	2.072	1.989	1182.72	1.812	2.370	2.295
4	643.72	0.836	1.006	1.190	596.24	0.996	1.215	1.309
5	666.06	1.643	2.012	2.057	622.78	1.614	1.932	1.989
6	720.52	1.046	1.415	1.547	610.21	0.697	1.165	1.224
Mean	741.46	1.462	1.837	1.938	727.04	1.505	1.811	1.943
S.D	144.17	0.557	0.645	0.505	226.41	0.533	0.680	0.549

13.c Ground Reaction Analysis of College Subjects

Subject	Fast				Change-Up			
	a	b	c	d	a	b	c	d
2	667.46	1.066	1.176	1.377	755.43	1.086	1.225	1.428
3	751.24	1.574	1.703	1.887	763.81	1.146	1.444	1.564
4	907.63	1.075	1.225	1.496	957.90	1.277	1.434	1.717
5	636.73	1.345	1.902	1.887	632.55	1.783	2.420	2.397
6	1111.50	1.135	1.633	1.598	1167.35	1.086	1.614	1.581
Mean	814.12	1.239	1.528	1.609	866.44	1.224	1.594	1.691
S.D	196.28	0.219	0.315	0.228	189.48	0.292	0.423	0.360