THE HIGH JUMP AS PERFORMED BY THE 1979 UNITED STATES OUTDOOR FEMALE RECORD HOLDER: A BIOMECHANICAL ANALYSIS

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

IN THE GRADUATE SCHOOL OF THE

TEXAS WOMAN'S UNIVERSITY

COLLEGE OF HEALTH, PHYSICAL EDUCATION,

AND RECREATION

BY

IRIS FUMIKO KIMURA, B.S., M.S.

DENTON, TEXAS

AUGUST 1981

ACKNOWLEDGMENTS

Acknowledgments are extended . . .

. . . to Dr. Marilyn Hinson for her guidance and suggestions throughout the development of this study;

. . . to the members of the dissertation committee, Dr. Aileene Lockhart, Dr. Bert Lyle, Dr. Jane Mott, and Dr. Joel Rosentswieg, for their interest, recommendations, and suggestions during the preparation of the dissertation;

. . . to Louise Ritter who participated in the study and extended the knowledge in the high jump;

. . . to my family for their encouragement and support;

. . . to my friends, Sherril York, Martha Scott, Sandy Funk, Barbara Peterson, Diane Duea, and Elizabeth Kelly for their support, encouragement, and comic relief;

. . . to Laurie Hammett for typing, proofreading, and many other extras.

TABLE OF CONTENTS

Chapter

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

ORIENTATION TO THE STUDY

Introduction

The Fosbury flop was introduced at the 1968 Olympic games where Dick Fosbury received the gold medal for his performance in the high jump. Since that time the Fosbury flop has become so popular that in the United States females who jump at the school or national level rarely use anything other than this technique (Santos, 1968). In Australia, all females and the majority of males who perform at the national level use the Fosbury flop (VanEs, 1979). The current male and female high jump world record holders both use the Fosbury flop technique.

Until recently, most of the studies conducted on the Fosbury flop high jump technique have been of a theoretical nature. Since the technique involves a curved approach run, the usual two-dimensional cinematographic procedures do not adequately record the movements involved (Dapena, 1980). The few experimental cinematographic studies that have been done on the Fosbury flop high jump technique have all been of males. Furthermore, only two biomechanical studies on female Fosbury flop jumpers have been located. Neither study involved subjects of world class caliber. In one study, a force-plate was utilized, and in the other, a single camera which recorded only the horizontal and vertical components of the jump was employed. Three-dimensional motion photography and subsequent analysis can aid in determining efficient and inefficient use of biomechanical principles and thus help females performing the Fosbury flop improve their high jump technique.

Purpose of the Study

The general purpose of the study was to provide information concerning the mechanics exhibited in the Fosbury flop high jump technique of a female using three-dimensional motion photography with subsequent biomechanical analysis.

Statement of the Problem

The problem was to investigate selected mechanical factors involved in the performance of the high jump by a single female subject. The subject was a female world class athlete enrolled at the Texas Woman's University, Denton, Texas, during the 1979-1980 academic year. She was filmed by two cameras at a rate of 200 frames per second while performing the high jump using the Fosbury flop technique. The data collected were subsequently subjected to biomechanical analysis. Results of the analysis were compared with biomechanic literature on the Fosbury flop high jump technique.

Research Questions of the Study

The researcher investigated the following specific questions:

1. What postural keys were displayed during the jumps?
    a. height of the lead knee immediately before the plant foot left the ground as measured by the angle between the thigh and the trunk.
    b. angle of the body relative to the right horizontal and the height of the arms as measured by the angle between the trunk and the upper arm immediately before the plant foot left the ground.
2. Was the arm action displayed by the subject biomechanically efficient regarding conservation of momentum?
3. Did the linear velocity of the approach affect the vertical angle of lift?
4. Where was the center or gravity during the penultimate step? Did this affect the angle of lift over the cross bar?
5. How long was the plant foot on the ground?

6. How did the velocity of the lead knee affect the height of the jump?
7. What was the displacement of the thigh of the lead knee in relation to the horizontal? At what angle was the knee of the lead leg flexed immediately before the plant foot left the ground?
8. What was the amount of flexion in the knee of the plant leg while it was on the ground?

All kinetic analyses pertained to the penultimate and take-off steps.

Definitions and/or Explanation of Terms

For the purpose of clarification, the following definitions and/or explanations of terms were established for use in the study:

A. Biomechanics:

"Mechanics involves the study of forces and their effects. The application of these mechanical principles to human and animal bodies in movement and at rest is biomechanics" (LeVeau, 1977, p. 1).

B. Fosbury flop technique:

"The jumping style created by Dick Fosbury in which the jumper approaches the bar with a forward run, facing the bar. Then he reverses his position so that during the flight and bar clearance his back is next to the bar and his face is pointed in the direction of the sky" (Lundmark, 1973, p. 5).

C. Penultimate stride or step:

The step prior to the last step (Lyle, 1979).

D. Three-Dimensional Motion Photography (Cinematography):

"Cinematography involves the use of the camera to record motion for subsequent kinesiological and/or biomechanical analysis" (Logan & McKinney, 1970, p. 195). Simultaneous use of two cameras at different angles permits calculation of forces and moments three-dimensionally (Plagenhoff, 1971, p. 7).

Delimitations of the Study

The study was subject to the following delimitations:

1. One female athlete twenty-two years of age who attended the Texas Woman's University, Denton, Texas, during the 1979-1980 academic year.
2. The reliability, objectivity, and validity of the three-dimensional cinematographic techniques and analysis procedures.
3. The accuracy of filming the subject's performance with two cameras located so that their optical axes intersected and were perpendicular to each other.

4. The equipment selected for use in the filming, and in the analysis of the films.
5. The accuracy of the point-and-line drawings and tracings of selected frames from the film of the subject.

Chapter II presents the literature reviewed which is related to the investigation.

CHAPTER II

REVIEW OF RELATED LITERATURE

A review of the related literature did not yield any evidence that the problem of this study has been investigated in the manner described in this dissertation. No research was found in which the object was to study women performing the Fosbury flop technique of high jumping using the three-dimensional cinematographic technique of data collection. Basic research of the Fosbury flop falls into one or more of the following categories: 1) studies performed on men; 2) the use of one or more cameras; and 3) descriptive studies of the Fosbury flop technique. This review of literature includes biomechanical studies concerning the Fosbury flop technique.

Peiniger (1969) "investigated the biomechanical characteristics of good and fair women high jumpers" (p. 32). The variables studied were: The path of the center of gravity; approach, transfer, and take-off velocities; projection angle; and angle and angular velocity of the kicking leg during take-off.

The subjects were four females aged fifteen to nineteen years who participated in a regional track and field meet at Gettysburg, Pennsylvania, in the spring of 1968. The two performers who achieved heights greater than five feet were identified as good jumpers and those who achieved heights of four feet but no greater than five feet were identified as fair jumpers. They were filmed by a sixteen millimeter (16 mm) Hycam variable speed camera at a rate of eighty frames per second during each of four trials. A Vanguard Motion Analyzer was used to analyze the two trials in which the competitors reached their maximum heights without displacing the cross bar.

A computer program was used for the calculation of the measurements. The findings follow:

1. The height of the jumper appeared to be directly related to the height achieved on the jump.
2. The two good jumpers did not demonstrate identical patterns of mechanics in the jump.
3. The good jumpers projected their centers of gravity a greater vertical distance than the fair jumpers.
4. Velocity and change in velocity during the approach and take-off phases of the jump showed no significant correlation with the height of the jump for good and fair jumpers.
5. Increased distance and decreased time of the approach were related to the velocity of the approach, but did not differentiate between the good and fair jumpers.
6. Decreased time in contact with the ground prior to take-off indicated an increased height of the jump, which differentiated one good jumper from the two fair jumpers.

7. Angular displacement of the kicking leg at take-off was not related to the height of jump for the good and fair jumpers.
8. Greater angular velocity of the kicking leg differentiated one good jumper from the two fair jumpers. (Peiniger, 1969, pp. 32-33)

Peiniger concluded that the variables studied did not significantly differentiate between good and fair jumpers.

Fix (1970) investigated the effect of approach velocity, leg spring, leg strength, and class on the height jumped and the jumping method used. The subjects were ninth grade boys enrolled in two physical education classes at Woodrow Wilson High School in Portland, Oregon. The twenty-two boys in one class and thirty-nine in the other class were randomly assigned to one of two methods of jumping, the Fosbury flop or the straddle roll. Before any instruction was given all sixty-one boys were asked to high jump at a height all could clear to give insight as to the boys previous instruction and jumping method preference.

The investigator instructed both groups for four weeks on alternate days. A Dillion dynamometer was used to measure leg strength and the vertical jump and reach test was used to measure leg spring. These tests were conducted during the four week training period when rain prevented jumping practice. During the fifth week each subject's highest jump was recorded along with the speed of approach of that jump.

Statistical analysis of the results showed significant correlation at the .05 level of significance between the following variables: speed of approach with leg strength, height jumped, and method of jumping; leg spring with leg strength; and height jumped with method of jumping and class. The regression analysis showed that the significant predictor variables of height jumped were speed of approach, class, and leg spring, respectively. A discriminant analysis of the difference between the mean heights showed that speed of approach proved to be the significant variable to differentiate between height jumped by both methods.

Hay (1973) investigated the effect of jumping style on the location of the center of gravity of one male athlete. The study was conducted in the Biomechanics Laboratory at the University of Iowa. The subject stood on the top of a trestle and assumed the best starting position for the execution of each of the following jumps: 1) scissors; 2) Western roll; 3) Eastern cut-off; 4) back layout; 5) Fosbury flop; 6) straddle; and 7) front pike or jackknife. The location of the athlete's center of gravity relative to the cross bar was calculated from photographs taken during each jump.

Hay studied the location of the center of gravity because he believed that the height of a jump was dependent upon the sum of three vertical distances. The first of these was the height of the center of gravity at take-off (H_1) and its dependence upon the athlete's physique and his body position the instant he leaves the ground. Height can be optimally achieved by a tall, long legged athlete (high center of gravity) whose arms are stretched overhead. The second vertical component was the distance the center of gravity is elevated during the flight (H_2), which is dependent upon the athlete's vertical velocity at take-off. The vertical velocity is a product of 1) vertical velocity at foot plant, and 2) any changes in vertical velocity made by altering the vertical impulse. (Vertical impulse is a product of the vertical forces and the length of time they are exerted.) As stated by Hay, "optimum take-off time in the high jump lies somewhere between .13 and .17 seconds for most jumpers" (1973, p. 79). The third component resulted from the jumper's efficiency in clearing the bar and his body position at the peak of the jump (H_3). Optimum clearance involves keeping the center of gravity near the bar by wrapping the body around it. Biomechanically, the most efficient position allows the center of gravity to pass below the bar. This position is represented by a positive H_3 value. When the center of gravity passes level with the cross bar, a zero value is observed. Thus, a negative H_3 value indicates an inefficient jump and the larger the negative value the more inefficient the jump.

Results of this study indicated that the most efficient method of clearing the cross bar was the jackknife or front pike position which had a theoretical optimum H_3 value of 10.4 inches. In descending order the next best positions were straddle with an H_3 value of 7.0 inches; Fosbury flop with an H_3 value of 3.3 inches; back layout with an H_3 value of -2.4 inches; Eastern cut-off with an H_3 value of -2.6 inches; Western roll with an H_3 value of -3.6 inches; and scissors with an H_3 value of -6.0 inches.

Kuhlow (1973) conducted a study to identify the takeoff features which revealed a "techno-specific relation" between the Fosbury flop and straddle; i.e., characteristics which significantly differentiate jumpers of both high jump techniques. The subjects were forty women high jumpers, twenty of whom employed the Fosbury flop, and twenty who used the straddle technique. They were assigned to groups of ten and classified according to ability. Group one was made up of women who attained heights ranging from 1.55 to 1.65 meters (M), with the straddle technique; group two consisted of women who jumped at heights between 1.30 to 1.40 M with the straddle technique. Group three included women who were able to jump 1.55 to 1.65 M using the Fosbury flop; group four was comprised of women who jumped heights between 1.30 to 1.40 M using the Fosbury flop technique.

Following the successful jump of each subject, the cross bar was raised in five centimeter (cm) increments. A Kistler force-place was used to measure the dynamic take-off features. The following characteristics of the take-off were investigated:

> (a) the time of take-off, (b) a quotient of two vertical forces; the maximum vertical force recorded during the initial impact of the foot with the ground and the maximum vertical force recorded later in the take-off, (c) the temporal position of this latter force in relation to the time needed for the take-off, (d) an indicator of the distribution of the vertical forces, (e) the vertical impulse, (f) an indicator of the take-off economy, and (g) the reduction in the horizontal velocity during the take-off. (Kuhlow, 1973, p. 403)

The analysis of variance revealed that the time of take-off was a "techno-specific feature" (1973, p. 403). This was determined by noting the velocity of the run prior to take-off.

Comparison of the positive acceleration force to the negative vertical acceleration revealed that the good jumpers of the Fosbury flop and straddle techniques had a higher positive vertical acceleration than did the poor jumpers of either technique; the good Fosbury flop jumpers also displayed a "smaller negative vertical acceleration impulse" (1973, p. 407). The good jumpers using the Fosbury flop and straddle techniques exhibited a "high reduction of the horizontal velocity" (p. 408) and high take-off economy. The reduction of the horizontal velocity of the good jumpers of each technique was 1.9 meters per second (m/sec). This was the result of a high negative horizontal acceleration impulse. The reduction of the horizontal velocity of the poor jumpers was 1.4 m/sec.

A nonlinear regression analysis of the "time of take-off, the relative temporal position of the positive vertical acceleration force, and the velocity of the run-up prior to take-off" (p. 408) was done to examine the relationship of these parameters and the height of the jump. The straddle jump was influenced by the time of take-off and the Fosbury flop by the velocity of the run-up. One standard deviation increase in the take-off time and run-up velocity improved the height of the straddle and Fosbury flop jumps 1.6 and 2.4 inches, respectively.

Lundmark (1973) investigated the mechanical factors involved in the Fosbury flop and the straddle high jump techniques. The subjects were two males, twenty-three and twenty-five years old. They were selected because they represented each of the jumping styles and performed them optimally, based on the physical laws involved. The subjects were filmed with a super eight millimeter film camera at a rate of 54 frames per second while they performed the jumps. The best attempt of each of the jumpers was analyzed and then compared one with the other.

Results of the study indicated that a higher percentage of the Fosbury flop jumper's force was used to elevate his center of gravity vertically due to the approach pattern "and the small amount of force required for the vertical and frontal rotations" (p. 46). The Fosbury flop approach velocity was very high due to the above factors and the easily assumed take-off position. The approach velocity, which "is mainly limited by the jumper's leg strength" (p. 46), had a substantial influence on the maximum height achieved by the jumper's center of gravity. The jumper using the Fosbury flop technique had an approach velocity at take-off (foot plant) which was 2.5 m/sec faster than that of the straddle jumper. The Fosbury flop jumper exceeded the height cleared by the straddle jumper.

The straddle technique for bar clearance is considered difficult when compared with the Fosbury flop technique for the following reasons. The Fosbury flop jumper's curved path facilitates the flight over the bar as the parabolic curve permits a landing away from the bar. The athlete also crosses the bar in a symmetrical pattern which allows his center of mass to pass below the bar. The straddle jumper, however, is unable to do this since the bar is crossed in a lengthwise position.

Dapena (1980) conducted a three-dimensional cinematographic investigation of the mechanics of translation in the Fosbury flop high jump technique. The subjects were six male high jumpers with marks between 1.98 meters (M) and 2.13 M during the study. Five of them were filmed with Beaulieu and Canon Reflex motion-picture cameras during an official track meet held in Vallehermoso Stadium, Madrid, Spain. The sixth subject was filmed with Locam and Kodak motion-picture cameras during a training session in Iowa City, Iowa. One camera was placed overhead and the other perpendicular to the high jump cross bar. Camera frame rates were set at 64 frames per second (fps) during both filming sessions. A Vanguard Motion Analyzer was used to analyze the film of the two best jumps of each subject from a total of twelve trials.

An orthogonal coordinate system using X, Y, and Z axes was fixed to the ground and used to define twenty-one body landmarks. Cubic spline functions were used to smooth the raw data and to interpolate values for intermediate times between frames since the film from the cameras did not correspond exactly because of lack of mechanical synchronization of the cameras. These values were used to compute the center of gravity of each athlete during various phases of the jump and, in turn, these center of gravity findings were utilized to determine horizontal velocities and vertical velocities at touch down and take-off.

Results of the study indicated that centripetal and centrifugal forces were small and similar for jumpers with straight and curved approaches. This finding negates the hypothesis that the purpose of the curved run-up is to produce centripetal force during the take-off phase. However, at touch down athletes with a curved approach had a more severe lean toward the center of the curve than those with a straight run-up; this could be the reason for the curved approach. All jumpers exhibited a negative vertical component of velocity during touch down. Following take-off, an absolute angle between 40 and 48 degrees was made by the "initial trajectory of the parabolic path of the center of gravity" (p. 43). The degree of flexion of the knee of the take-off leg varied between 126 and 140 degrees (minimum angle). The study showed that the Fosbury flop technique of high jumping allowed one jumper to clear the cross bar while his center of gravity remained at the same level as the cross bar.

Dapena (1980) investigated the mechanics of rotation using the same film generated in his previous study (noted above); thus, the subjects, filming procedures, analysis and X, Y, Z coordinate system used to define twenty-one body landmarks of each subject were also the same. In this study, two other orthogonal coordinate systems were fixed to the ground. The X, Y, Z coordinate system was placed relative to the high jump cross bar. The A, B, Z coordinate system was placed relative to the final direction of the approach. The X, Y, A, and B axes were in the horizontal planes and the Z axes were vertical. The moment of inertia values of the body were calculated for each instant and coordinant system axis. Dapena also computed the average angular momentum vector for each time interval.

Intersubject comparisons were facilitated by dividing the angular momentum values for each subject by the square of his standing height and his mass. Instantaneous angular momentum values at touch down (TD) and take-off (TO) were calculated by averaging the angular momentum values for the nonsupport phase prior to TD and TO.

Results of the study indicated that most of the angular momentum present at TO was produced during the TO phase. This is contrary to the belief that much of the angular momentum necessary for bar clearance was produced before the TO phase. Subjects who used curved run-ups exhibited greater rotation in the desired negative direction before the TO phase. The curved run-up also facilitated the lean toward the center of the curve at TD which increased the "vertical range of motion of the center of gravity during the TO phase" (Depena, 1980, p. 53).

CHAPTER III

METHODS AND PROCEDURES

The general purpose of the study was to provide information concerning the mechanics exhibited in the Fosbury flop high jump technique of a female using three-dimensional motion photography with subsequent biomechanical analysis. Procedures followed in the development of the study were: (a) preliminary procedures; (b) procedures followed in the selection of the subject; (c) procedures followed in filming the Fosbury flop; (d) procedures followed in analyzing the Fosbury flop high jump technique; and (e) preparation of the final written report.

Preliminary Procedures

Specific preliminary procedures were completed prior to the actual filming and analysis of the Fosbury flop high jump technique. Information from all available documentary and human resources was studied. A review of the related literature led the investigator to conclude that there was no study identical to the present investigation. A tentative outline was developed and presented to the members of the dissertation committee, and revisions were made in accordance with their suggestions. Approval was obtained from the Texas Woman's University Human Subjects Review Committee. The outline of the study was then filed in the form of a prospectus in the Office of the Provost of the Graduate School.

Procedures Followed in the Selection of the Subject

The films selected for study were made at the Texas Woman's University during the 1980 spring semester. The female subject was the 1979 United States Outdoor record holder in the high jump. The subject was selected for study and subsequent biomechanical analysis because of her world class ability in the Fosbury flop high jump technique. A film clearance permission form was signed by the subject and is included in the appendix.

Procedures Followed in Filming the Fosbury Flop

Filming at the Texas Woman's University was done by two graduate assistants and the investigator. Locam and Photosonics I high speed cameras, each equipped with an Angeneaux zoom lens, were used with frame rates of 200 frames per second and a 1/3 shutter fraction. A meter stick was held in each field of vision and filmed to provide a multiplication factor necessary for subsequent analysis. Kodak Black and White Tri-X Reversal film with an ASA of 200 was utilized for the filming. The light meter of a Canon TL camera was used to determine the appropriate f-stop setting (f=11). The subject was filmed from side (ninety degrees to the cross bar) and front (parallel to the cross bar). A ninety degree angle separated the cameras' optical axes from distances of 37 feet 2 3/4 inches and 46 feet 7 3/4 inches, respectively. The film was developed by Educational Processing in Dallas, Texas.

Procedures Followed in Analyzing the Fosbury Flop

The film was viewed initially on a Lafayette Stop Action Motion Projector. The investigator's digitizing reliability was established for four trials at .97 for the side view and .99 for the front view. The path of the subject's center of gravity was determined for each jump. The two trials which exhibited the highest center of gravity and the one trial with the lowest center of gravity were selected for analysis.

The films of the three trials were utilized for further quantitative biomechanical analysis and were viewed frame-by-frame on the Lafayette Stop Action Movie Projector which projected each frame through a system of three 45 degree angle mirrors onto a glass top viewing table covered with tracing paper. The viewing system was adjusted so that the film images were as near as possible to one-fifth life size; a fixed point common to both camera views of the jump was also visible.

The trials were analyzed every five frames by digitizing the joint centers referred to by Plagenhoef (1971) as reference points. The foot, shank, thigh, trunk, pelvis, shoulder, upper arm, and forearm were analyzed during the penultimate step and the plant step of the Fosbury flop high jump.

The joint centers were digitized, following the Plagenhoef (1971) link system, with a Numonics Graphics Calculator interfaced with a Dec-System 20 Computer. Digitized results from both camera views were merged frame by frame using the Texas Woman's University "KNMTC2.For" computer program on the Dec-System 20. Digitized results included information concerning the X and Y coordinate points of the joint centers, absolute angles (angles measured from the right horizontal), relative angles (angles measured in relation to the adjoining body segment), and length of the body segments.

The quantitative biomechanical analysis followed by utilizing the Hewlett-Packard 9810 A Calculator/Computer interfaced with a Hewlett-Packard Plotter. The velocities, computed through the use of the Texas Woman's University "LAMB.For" computer program on the Dec-System 20, were plotted with corresponding time intervals. A polynomial regression program was used to determine the curve of best fit. The data were presented in graphic and tabular form. Between trial comparisons were based on the graphed angles and velocities, centers of gravity, and corresponding time interval calculations. Interpretations of the data were made, and contrasts and similarities between the trials and existing research literature were discussed.

Preparation of the Final Written Report

Preparing the final report of the study included developing a topical outline for each chapter, writing the individual chapters, and revising the chapters according to committee members' suggestions. Findings were summarized, discussed, and interpreted. Implications of the research were made and a conclusion was determined. An appendix and selected references were developed with recommendations for further study being addressed. The results of the study are presented in Chapter IV.

CHAPTER IV

PRESENTATION OF THE FINDINGS

The findings of the study using three-dimensional motion photography for data collection to investigate the Fosbury flop technique of high jumping are presented in this chapter. Analysis of a female world class athlete's high jump technique consisted of kinematic information for the following body segments: (1) foot, (2) shank, (3) thigh, (4) pelvis, (5) trunk, (6) shoulder, (7) upper arm, and (8) forearm during the penultimate and take-off steps of the jumps. The findings of the study are presented under the headings of Quantitative Analysis and Comparison with the Literature.

Quantitative Analysis

Research question one: What postural keys were displayed during the jumps? Using a Lafayette Motion Analyzer, stick figures were made of the subject as she performed each jump. A protractor was used to measure the angles between the thigh and trunk, between the body and the right horizontal and between the trunk and upper arms at the last point of contact with the ground during the take-off step of each jump. These angles are presented in Table 1. The table reveals that: the height of the lead knee was greatest during jump two (2) and smallest during jump three (3); the angle of the body was least upright during jump three and most upright during jump one (1); the height of the left arm was greatest during jump two and smallest during jump three; and the height of the right arm was greatest during jump two and smallest during jump one.

Table 1

Key Postural Angles Displayed During the Jumps

		Postural Keys (in degrees)			
Jump	Height Jumped	Lead Leg Ht	Body Angle	Left Arm Ht	Right Arm Ht
1	5'10"	70	92	70	82
2	6'	65	95	74	103
3	6'2"[a]	83	98	56	88

[a]Subject did not successfully clear the cross bar.

Research question two: Was the arm action displayed by the subject biomechanically efficient regarding conservation of momentum? Using a Lafayette Motion Analyzer and a Numonics Graphics Calculator interfaced with a Dec-System 20/50 Computer, the three jumps were analyzed every five frames by digitizing the joint centers according to the Plagenhoef (1971) link system (see appendix). Digitized results from both camera views were merged frame by frame using the "KNMTC2.For" computer program from the biomechanics library. The resulting merged information was further subjected to analysis using the "LAMB.For" computer program, also from the biomechanics library, to compute segmental displacements and total body centers of gravity (CG). "M-LAB" (Knott, 1979), a computer modeling program was used to derive the velocities of the right upper arm. A fourth degree polynomial was used for all segments.

Table 2 presents the values of the velocities for the subject's right upper arm and the location of her center of gravity throughout the plant step. The table reveals that the first two jumps initially exhibited comparable velocity values and a similar change in direction beginning with position six (0.15 seconds) in jump one and position seven (0.175 seconds) in jump two. Velocity values of jump three were not comparable and did not indicate a similar change in direction. The height of the center of gravity was greatest in jumps one and two during position seven (0.175 seconds) and eight (0.2 seconds), respectively, and during position three (0.075 seconds) in jump three.

Figure 1 presents the smoothed velocity curve of the subject's right upper arm during the take-off step of the

Table 2

Comparison of Velocity Values for the Right Upper Arm with Height of Center of Gravity (CG)

Jump	Position	Time (in sec)	Velocity (in degrees/sec)	CG (in cm)
1	1	0.025	187.32	62.15
	2	0.05	355.93	84.20
	3	0.075	515.13	127.30
	4	0.1	403.73	51.11
	5	0.125	135.20	82.49
	6	0.15	-176.99	83.27
	7	0.175	-419.37	138.67
	8	0.2	-478.49	92.04
	9	0.225	-240.86	71.96
2	1	0.025	-465.99	66.58
	2	0.05	-10.99	64.66
	3	0.075	256.70	71.85
	4	0.1	359.74	117.63
	5	0.125	320.76	51.77
	6	0.15	162.41	95.52
	7	0.175	-92.66	87.84
	8	0.2	-421.81	129.70
	9	0.225	-802.40	67.63
3	1	0.025	181.07	69.71
	2	0.05	-54.04	101.70
	3	0.075	-195.72	142.32
	4	0.1	-290.67	47.47
	5	0.125	-385.58	93.12
	6	0.15	-527.13	90.67
	7	0.175	-762.04	99.16

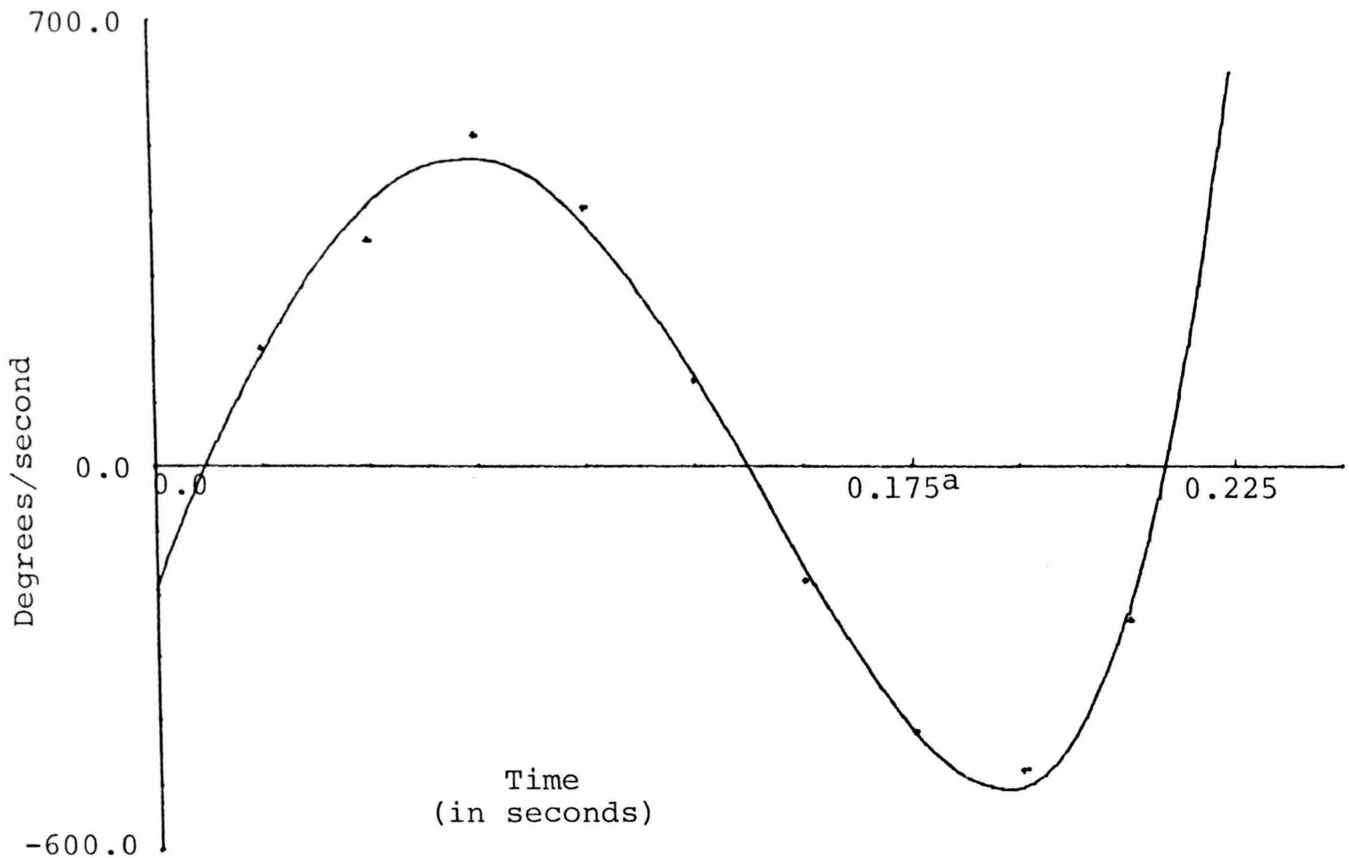


Figure 1. The smoothed velocity curve of the right upper arm during the take-off step of the first jump. ([a]Position where center of gravity was greatest.)

first jump. The graph indicates that the subject initiated extension and that the velocity of the body segment started at 187.32 degrees per second (dps) and decreased to -240.86 dps within 0.225 seconds (sec).

Figure 2 presents the smoothed velocity curve of the subject's right upper arm during the take-off step of the second jump. The graph reveals that the subject demonstrated a similar pattern of shoulder extension and that the velocity of the body segment started at -476.27 dps and decreased to -802.40 dps within 0.225 sec.

Figure 3 presents the smoothed velocity curve of the subject's right upper arm during the take-off step of the third jump. This graph indicates that the subject intiated shoulder flexion rather than extension and that the velocity of the body segment started at 181.07 dps and decreased to -762.04 dps within 0.175 sec.

Research question three: Did the linear velocity of the approach affect the vertical angle of lift? Linear velocity of the body was calculated beginning when first contact of the plant foot with the ground to the moment of take-off. The horizontal displacement of the subject's center of gravity was divided by time. Angle of take-off was calculated by dividing the horizontal difference (ΔX) by the vertical difference (ΔY) that the center of gravity

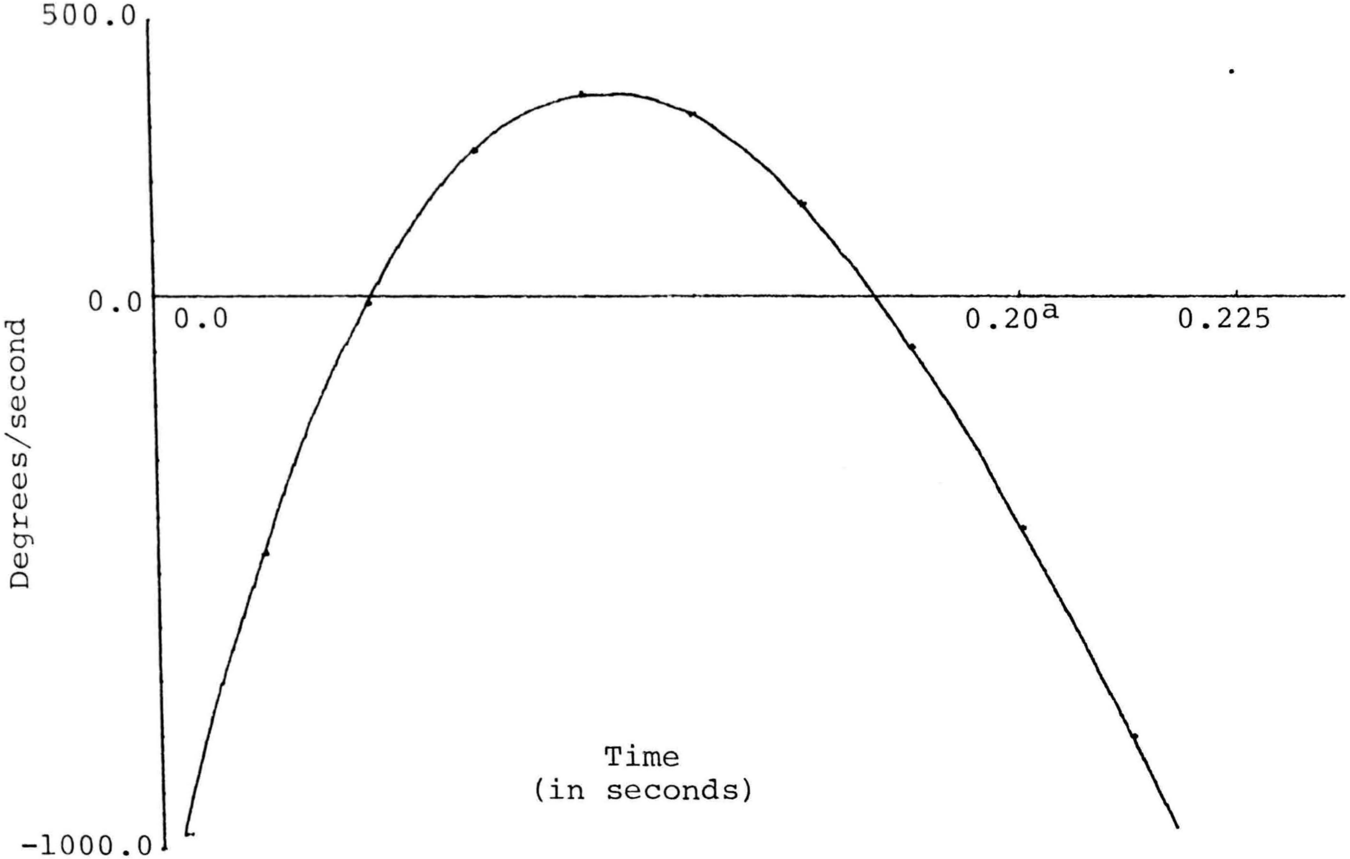


Figure 2. The smoothed velocity curve of the right upper arm during the take-off step of the second jump. ([a]Position where center of gravity was greatest.)

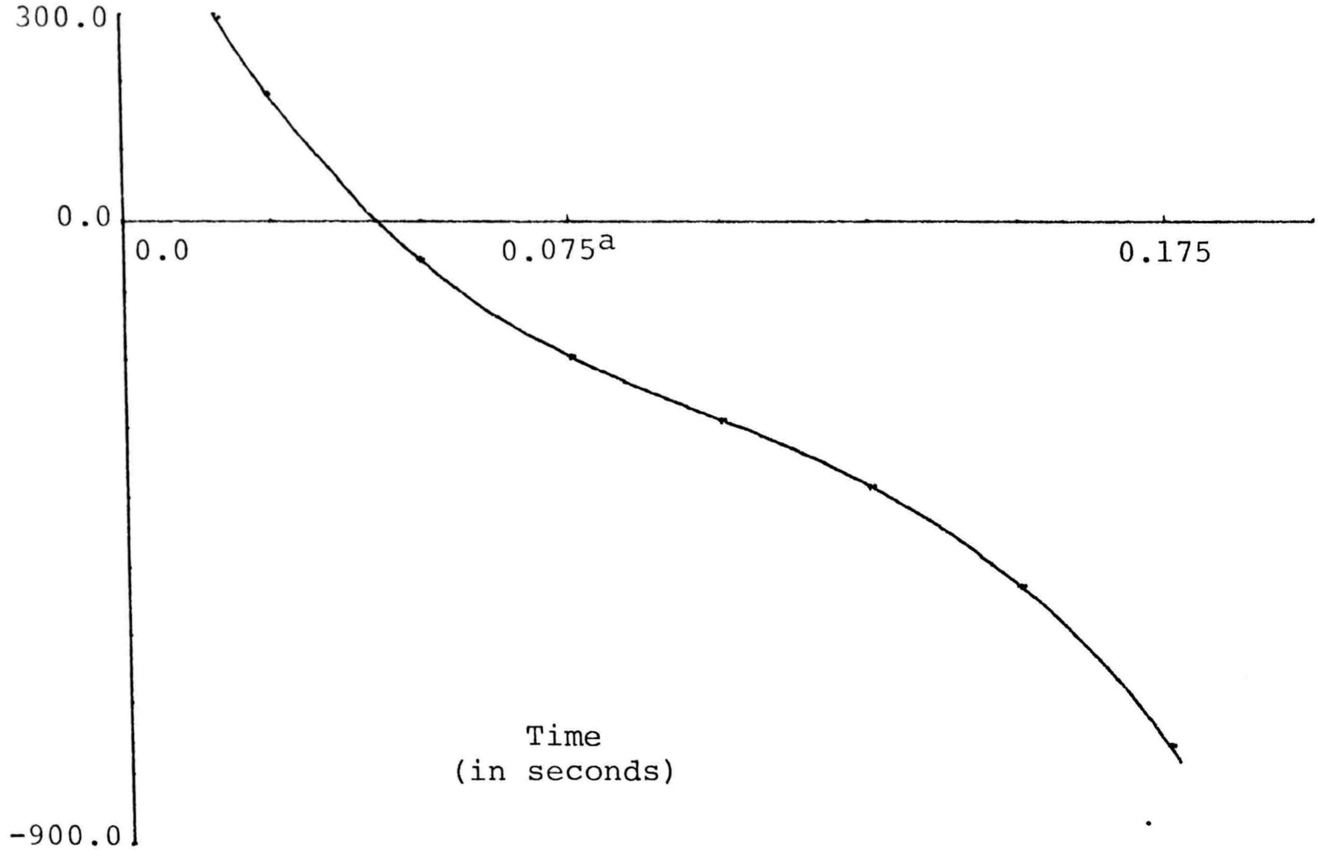


Figure 3. The smoothed velocity curve of the right upper arm during the take-off step of the third jump. ([a]Position where center of gravity was greatest.)

moved during 0.025 sec previous to take-off. The result of the calculation, slope, was then converted to degrees (arc tangent).

Table 3 presents a comparison between the linear velocity of approach and the angle of take-off of each jump. The table indicates that the linear velocity of approach was fastest during jump one and slowest during jump two. The angle of take-off was greatest during jump two and least during jump one.

Table 3

Comparison Between Linear Approach Velocity of the Body and Angle of Take-off

Jump	Linear Velocity (in m/sec)	Angle of Take-off (in degrees)
1	4.29	30.92
2	3.76	41.43
3	3.91	41.28

Research question four: Where was the center of gravity during the penultimate step? Does this affect the angle of lift over the cross bar? Utilizing the center of gravity (CG) data previously analyzed, the vertical displacement of the body was observed during the penultimate step of each jump.

Table 4 presents the angle of take-off, the subject's highest and lowest positions during the penultimate step, and the difference between these positions (vertical displacement). The table reveals that the angle of take-off was greatest in jump two and lowest in jump one. The lowest CG was seen during jump three and the highest during jump one. The CG traveled the greatest vertical distance during the penultimate step of jump three and the shortest vertical distance during jump two.

Table 4

Comparison of the Angle of Take-off (slope) with Center of Gravity High and Low Points and Their Differences

Jump	Take-off Angle[a]	CG Low Position[b]	CG High Position[b]	Vertical Displacement[b]
1	30.92	49.45	142.63	93.18
2	41.43	58.00	142.32	84.32
3	41.28	19.10	132.07	112.97

[a]Expressed in degrees.

[b]Expressed in cm.

Research question five: How long was the plant foot on the ground? Take-off time was calculated by counting the number of frames which elapsed while the subject's plant foot was in contact with the ground and dividing the result by the camera speed. Table 5 presents the take-off time (in sec) for each jump. The table indicates that the foot remained in contact with the ground longest during jump two and for the shortest time during jump one.

Table 5

Take-off Times for the Three Jumps

Jump	Take-off Time (in sec)
1	0.175
2	0.19
3	0.185

Research question six: How did the velocity of the lead knee affect the height of the jump? During the take-off phase of each jump, the angular displacement of the lead leg was measured with a protractor. "M-LAB" (Knott, 1979), a computer modeling program, was incorporated to derive the velocities of the right (leading) thigh. A fourth degree polynomial was used. Velocities for each jump were then calculated from the first derivative and plotted with corresponding time intervals.

Figure 4 presents the smoothed velocity curve of the subject's right thigh during the take-off step of the first

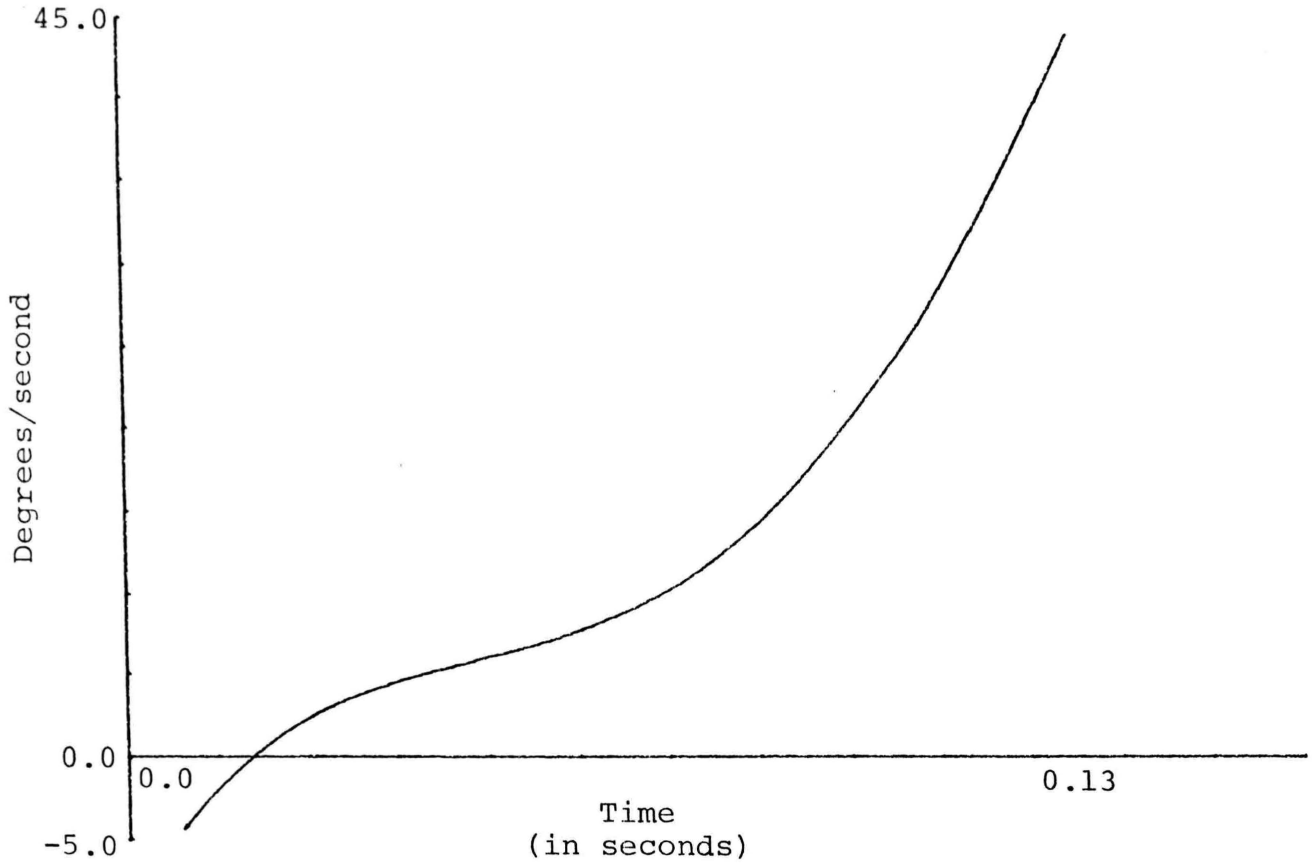


Figure 4. The smoothed velocity curve of the right thigh during the take-off step of jump one.

jump. The graph indicates that the velocity of the thigh started at -1.840 degrees per second (dps) and steadily increased to 38.813 dps within 0.11 seconds.

Figure 5 presents the smoothed velocity curve of the subject's right thigh during the take-off step of the second jump. The graph reveals that the subject demonstrated a similar increase in thigh velocity which started at -2.613 dps and progressed to 24.111 dps within 0.11 seconds.

Figure 6 presents the smoothed velocity curve of the subject's right thigh during the take-off step of the third jump. The graph shows an oscillation of velocity from -0.595 dps to 2.445 dps within 0.9 seconds.

Research question seven: What was the displacement of the thigh of the lead knee in relation to the horizontal? At what angle was the knee of the lead leg flexed immediately before the plant foot left the ground? Absolute angular positions of the thigh of the lead (right) leg and angles of knee flexion were determined at take-off for comparison in Table 6. The table reveals that the thigh was highest during jump two and at its lowest during jump three. The knee was flexed most during jump one and least during jump three.

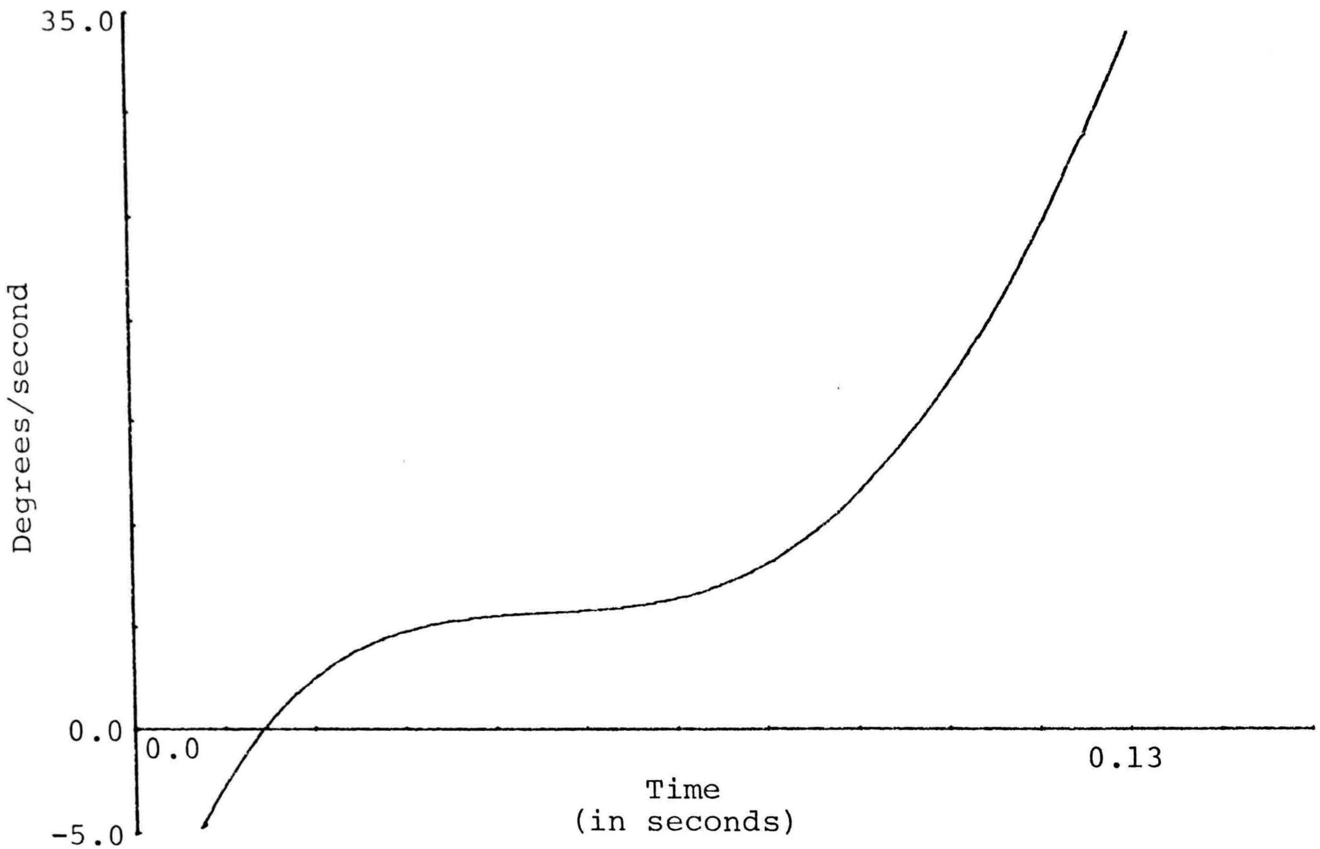


Figure 5. The smoothed velocity curve of the right thigh during the take-off step of jump two.

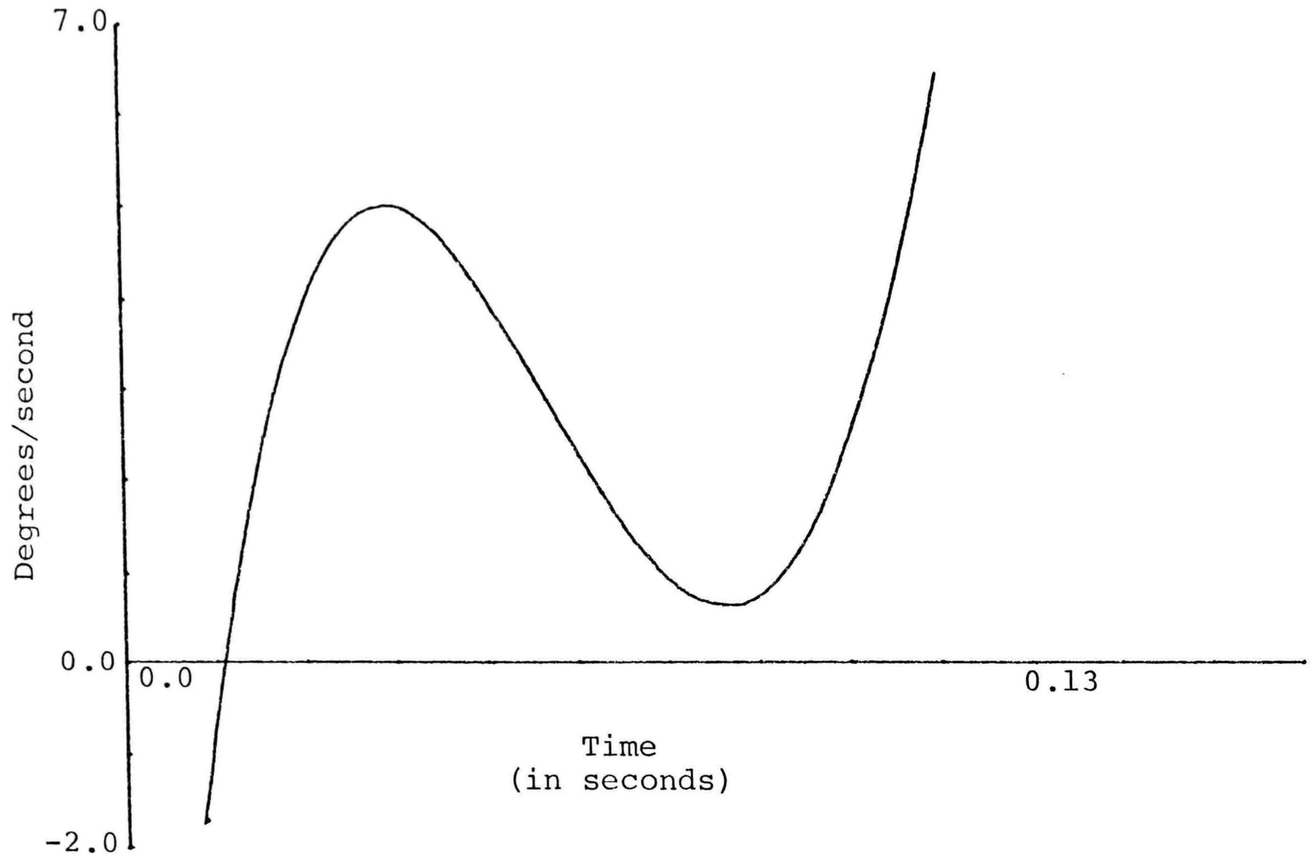


Figure 6. The smoothed velocity curve of the right thigh during the take-off step of jump three.

Table 6

Comparison of Absolute Angular Position of the Lead (Right) Thigh with Right Knee Flexion at Take-off

Jump	Thigh Position (in degrees)	Knee Flexion (in degrees)
1	7	107
2	15	109
3	6	117

Research question eight: What was the amount of flexion in the knee of the plant leg while it was on the ground? The angles of knee flexion of the plant leg were measured with a protractor and are presented in Table 7. The table indicates that the knee of the plant leg flexed most (minimum angle) during jump three and least (maximum angle) during jump two.

Comparison with the Literature

As noted in Chapter II of this dissertation, there is no research literature on women performing the Fosbury flop high jump technique which used the three-dimensional cinematographic technique of data collection. Previous studies of this type have either been limited to men, or have employed force-plates and single cameras to collect data.

Table 7

Plant Foot Angles of Knee Flexion

During Take-off

Jump		
1	2	3
Knee Flexion Angles (in degrees)		
160	162	168
160	163	163
157	165	166
150	149	158
140	142	150
139	140	150
136	137	147
135	133	143
134[a]	130	138[a]
135	129[a]	140
138	130	142
139	133	143
142	134	146
146	137	154
148	139	158
159	143	165
161	152	177
172	163	180[b]
177[b]	172	
	178[b]	

[a]Minimum angle.

[b]Maximum angle.

For the purpose of this study, most comparisons of the subject's high jumping technique were made with those of males.

Dapena's (1980) three-dimensional cinematographic investigation of the mechanics of translation in the Fosbury flop high jump technique identified the following parameters: at take-off the horizontal component of velocity varied between 6.3 and 7.9 meters per second (m/sec); the take-off angle varied between 40 degrees and 48 degrees; take-off time (time plant foot was on the ground) ranged from 0.14 to 0.20 sec with a mean of 0.16 sec; and during the take-off phase the minimum angle of flexion in the knee of the take-off leg varied between 126 degrees and 140 degrees with a mean angle of 133 degrees. This study revealed the following parameters: the horizontal velocities at take-off ranged from between 3.76 and 4.29 m/sec; the take-off angles ranged from between 30.92 degrees to 41.43 degrees; take-off time varied between 0.175 and 0.19 sec with a mean of 0.183 sec; and the minimum angle of flexion in the knee of the take-off leg recorded in jumps one, two, and three were 134 degrees, 129 degrees, and 138 degrees, respectively, with an average angle of 133 degrees.

Peiniger's (1969) cinematographic study of good and fair women high jumpers revealed a take-off time ranging from 0.17 sec to 0.23 sec with a mean time of 0.2025 sec for good jumpers. Take-off times ranged between 0.20 and 0.21 sec with a mean time of 0.2075 sec for fair jumpers. In this study, take-off times identified in jumps one, two, and three of the present study varied between 0.175 sec and 0.19 sec with an average time of 0.183 sec.

Kuhlow's (1973) study comparing take-off features of Fosbury flop and straddle roll technicians reported that good Fosbury flop performers displayed an average take-off time of 0.17 sec and poor performers had an average time of 0.19 sec. Take-off times reported for jumps one, two, and three in this study were 0.175 sec, 0.19 sec, and 0.185 sec, respectively.

Chapter V presents a summary of the investigation, findings and discussion as well as a conclusion of the study. Recommendations for further studies are also given.

CHAPTER V

SUMMARY, FINDINGS, CONCLUSION, DISCUSSION, AND RECOMMENDATIONS FOR FURTHER STUDIES

In this chapter, a summary of the investigation, findings, discussion of the findings, and a conclusion are presented. Recommendations for further studies are also made.

Summary of the Investigation

A review of literature has indicated the need for research on the Fosbury flop technique of high jumping, and an even greater need to study women who perform this method of high jumping. As noted earlier, three-dimensional motion photography is the most viable means of collecting this type of data. The knowledge gained from this research can aid females performing the Fosbury flop improve their high jump technique.

It was the researcher's desire to conduct a study to provide basic information concerning the mechanics exhibited in the Fosbury flop high jump technique of a female and to use three-dimensional motion photography to collect the data for subsequent biomechanical analysis.

The researcher investigated the following specific questions involved in the performance of the high jump by a single female subject:

1. What postural keys were displayed during the jumps?
    a. height of the lead knee immediately before the plant foot left the ground as measured by the angle between the thigh and the trunk.
    b. angle of the body relative to the right horizontal and the height of the arms as measured by the angle between the trunk and the upper arm immediately before the plant foot left the ground.
2. Was the arm action displayed by the subject biomechanically efficient regarding conservation of momentum?
3. Did the linear velocity of the approach affect the vertical angle of lift?
4. Where was the center of gravity during the penultimage step? Does this affect the angle of lift over the cross bar?
5. How long was the plant foot on the ground?
6. How did the velocity of the lead knee affect the height of the jump?
7. What was the displacement of the thigh of the lead knee in relation to the horizontal? At what angle

was the knee of the lead leg flexed immediately before the plant foot left the ground?

8. What was the amount of flexion in the knee of the plant leg while it was on the ground?

Specific procedures were adhered to in conducting the study. The procedures followed in the development of the study were as follows: (a) Preliminary procedures, (b) Procedures followed in the selection of the subject, (c) Procedures followed in filming the Fosbury flop; (d) Procedures followed in analyzing the Fosbury flop high jump technique, and (e) Preparation of the final written report.

The films selected for analysis were made at the Texas Woman's University during the 1980 spring semester. The female subject was the 1979 United States Outdoor record holder in the high jump. She was selected because of her world class ability in the Fosbury flop technique of high jumping.

Findings of the Investigation

The findings of the study indicated that:

1. The following postural keys were noted immediately before the plant foot left the ground: the angle of the body relative to the right horizontal was least upright during jump three and most upright during jump one; the

lead knee was highest during jump two and lowest during jump three; the left and right arms were highest during jump two and lowest during jumps three and one, respectively.

At the end of the last stride the athlete moved her trunk from a forward incline to a backward incline in an apparent effort to lengthen the horizontal and vertical displacement of the center of gravity and, thus, lengthen the time for her to coordinate her take-off movements. In none of the jumps was she able to achieve a position of the body which was less than 90 degrees to the horizontal. The lack of sufficient backward lean is regarded as the flaw in the athlete's technique.

The simultaneous forward and upward swing of the arm(s) and lead leg served three principle functions:

1. It increases the magnitude of the vertical forces exerted against the ground, the vertical forces that the ground exerts on the athlete in reaction, and thus the athlete's vertical velocity at takeoff.

2. It imparts angular momentum to the athlete's body. As the swing of the lead leg and arm(s) slows down, the angular momentum that these limbs possess is transferred to the body as a whole.

3. It increases the height of the athlete's center of gravity at the instant of takeoff (Hay, 1978, p. 438).

Hence, the high arm(s) and lead leg positions in jump two was the most beneficial to the movement.

2. Jumps one and two exhibited comparable increments of velocity and direction changes of the upper arm at the point where the center of gravity was the highest. Velocity values of jump three were not comparable nor was the pattern of motion.

Results of the investigation indicated that jump three with the cross bar set at six feet, two inches was substantially different from jumps one and two (five feet, ten inches and six feet, respectively). Aside from being the highest attempted, jump three was the only one missed of the three jumps selected for analysis.

The principle of conservation of angular momentum states that: "A rotating body will continue to turn about its axis of rotation with constant angular momentum, unless an external couple or eccentric force is exerted upon it" (Hay, 1978, p. 148).

Momentum was most efficiently conserved in jumps one and two as displayed by the subject's arm action. Shortly after take-off, the subject extended her arms to elevate the center of gravity. The center of gravity was highest near the end of the extension phase in both jumps. Because of the principle of conservation of momentum, angular momentum was transferred by this extension process. A body can only increase its moment of inertia and maintain angular momentum if it decreases angular velocity (Hay, 1978). Hence, when the subject's arms were extended, her moment of inertia was increased as the angular velocity of the arms was decreased. This was noted only in jumps one and two.

3. Jump one revealed the greatest linear velocity coupled with the lowest angle of take-off. Conversely, jump two indicated the slowest linear velocity coupled with the highest angle of take-off.

The ratio between the vertical and horizontal components of the velocity at the instant of take-off determines the take-off angle. Increased angles are seen with large vertical components and small horizontal components (Dapena, 1980). Although take-off angles found in this investigation did not closely coincide with those reported in the literature, jump two, which exhibited the greatest take-off angle, did show the smallest horizontal velocity component.

4. The center of gravity during the penultimate step was lowest during jump three and highest during jump one. Center of gravity positions were very similar for jumps one and two.

> If at the end of his penultimate stride the athlete has sunk low over his supporting leg and then taken a low, fast step onto his takeoff foot, his center of gravity is likely to have little or no downward vertical velocity at the instant this foot touches down. On the other hand, if by failing to sink low at the end of his penultimate step he makes his last step like those that have preceded it, the athlete's downward vertical velocity at touchdown is likely to be relatively large. (Hay, 1978, p. 427)

Jumps one and two were performed efficiently in this regard.

5. Take-off time ranged from between 0.175 seconds to 0.19 seconds. Resulting take-off times fell well within the limits reported in research involving women. These times were slower than take-off times reported for men of world class caliber who perform the Fosbury flop technique of high jumping. Hay (1978) stated that the shorter the time of take-off the greater the vertical life. In jump one, the take-off time was shortest.

6. The velocity of the lead thigh showed similar increases during jumps one and two but fluctuated between positive and negative during jump three. Because magnitude of vertical impulse is dependent, in part, on the velocity

of the lead thigh, it would appear that the first two jumps were performed more efficiently than jump three.

7. The thigh of the lead leg was raised to its highest position during jump two and to its lowest position during jump three. The knee of the lead leg was flexed most during jump one and least during jump three.

As mentioned above, the height of the lead leg affects the height of the center of gravity at take-off. Because the degree of flexion in the knee is proportional to the moment of inertia of the legs, the efficiency with which the leg was raised during jumps one and two was greater than for jump three.

8. The knee of the plant leg was flexed most throughout the take-off phase during jump three and least during jump two.

Dapena (1980) noted that the optimum angle of flexion in the knee of the plant leg is time-dependent, although he also indicated that coaches recommend a 140 degree angle. The minimum angle recorded in each jump during the present study was below this recommended limit of knee flextion (range = 129 to 138 degrees). The angles during jumps one and two did, however, closely approximate those actually found by Dapena (1980).

Conclusion

From the findings of this investigation it was concluded that the subject was biomechanically efficient in jumps one and two but not in jump three. The mechanics involved in the velocity and position of the lead knee; the arm action; the velocity of approach; the vertical angle of lift; the placement of the center of gravity; the time of take-off; and the flexion of the knee of the lead and plant leg compared favorably with the literature and can be used to describe efficient Fosbury flop technique.

Recommendations for Further Studies

The following suggestions are recommended for further investigation:

1. Film a comparable group of females performing the Fosbury flop technique of high jumping with three-dimensional motion photography.

2. Replicate the questions asked in this study and investigate other biomechanical factors involved in females performing the Fosbury flop technique of high jumping such as: (1) stride length, (2) angle of approach, (3) angular momentum, (4) angle of placement of the plant foot, and (5) path of the center of gravity throughout the jump.

APPENDIX

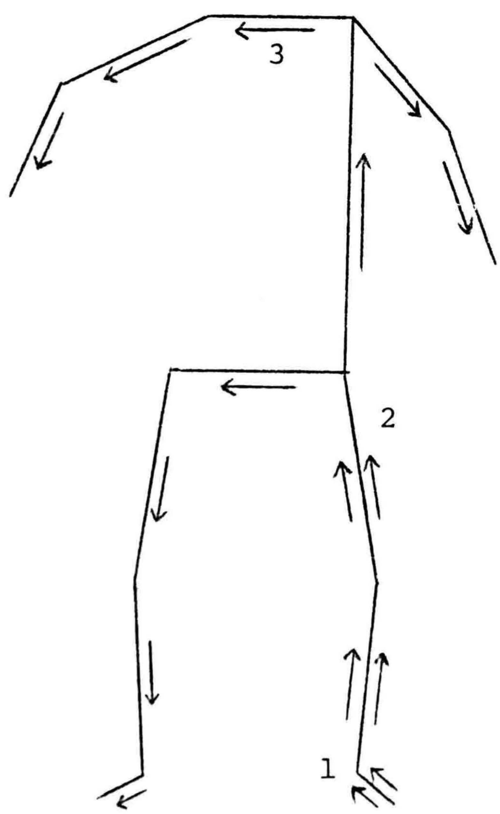
THE LINK SYSTEM DESCRIBED BY PLAGENHOEF

Starting from the left foot as the fixed point:

Link 1 = left foot, left shank, left thigh, hips, right thigh, right shank, right foot

Link 2 = left foot, left shank, left thigh, trunk, left upper arm, left forearm

Link 3 = left foot, left shank, left thigh, trunk, shoulders, right upper arm, right forearm



Fixed Point

Displacements of the Right Upper Arm

Jump		
1	2	3
Displacements		
84	71	91
74	67	101
110	59	97
105	86	76
108	91	71
116	80	69
112	93	76
91	92	
86	69	

Displacements of the Lead Knee

Jump		
1	2	3
Displacements		
-1	-0	-1
-4	-3	-5
0	-2	-3
-5	-4	-2
-7	-5	0
-10	-7	-2
-14	-9	-2
-17	-10	-5
-20	-12	-7
-39	-22	-11
-66	-35	-16
-74	-50	-35
-88	-67	-50
-100	-80	-70
-106	-93	-87
-112	-100	-97
-122	-105	-105
-127	-112	-114
-129	-116	-116
-129	-119	-120
-130	-121	-118
-130	-124	-113
	-125	-112

REFERENCES

REFERENCES

Bowerman, W. J. Coaching track and field. Boston: Houghton Mifflin Company, 1974.

Bunn, J. W. Scientific principles of coaching. Englewood Cliffs, New Jersey: Prentice-Hall, 1972.

Chu, D. Mechanics of the flop style high jump. Track and Field Quarterly Review, 1979, 79, 47.

Dapena, J. Mechanics of rotation in the Fosbury flop. Medicine and Science in Sports and Exercise, 1980, 12(1), 45-53.

Dapena, J. Mechanics of translation in the Fosbury flop. Medicine and Science in Sports and Exercise, 1980, 12(1), 37-44.

Fix, G. E. A study of contributing variables to two methods of high jumping. Unpublished doctoral dissertation, University of Portland, 1970.

Hay, J. G. Biomechanical aspects of jumping: the running jumps for height. In J. H. Wilmore & J. F. Keogh (Eds.), Exercise and Sport Sciences Reviews. New York: Academic Press, 1975.

Hay, J. G. The Biomechanics of sports techniques. Englewood Cliffs, New Jersey: Prentice-Hall, 1978.

Knott, G. D. Mlab--A mathematical modeling tool. Computer Programs in Biomedicine, October 1979, 10, 271.

Kuhlow, A. A comparative analysis of dynamic take-off features of flop and straddle. In S. Cerquiglini, A. Vernerando, & J. Wartenweiler (Eds.), Medicine and sport, biomechanics III, Karger, Basal, 1973.

LeVeau, B. Williams and Lissner: Biomechanics of human motion. Philadelphia: W. B. Saunders, 1977.

Logan, G., & McKinney, W. Kinesiology. Dubuque: Wm. C. Brown, 1970.

Lundmark, K. A comparative mechanical analysis of the Fosbury flop and straddle styles of high jumping. Unpublished master's thesis, Brigham Young University, 1973.

Lyle, B. Personal communication at the Texas Woman's University, Denton, Texas, fall, 1979.

Peiniger, M. A cinematographical analysis of women high jumpers. Unpublished master's thesis, The Pennsylvania State University, 1969.

Plagenhoef, S. Patterns of human motion: A cinematographic analysis. Englewood Cliffs, New Jersey: Prentice-Hall, 1971.

Santos, J. The plant and takeoff in the Fosbury flop. Track and Field Quarterly Review, 1979, 79, 48.

Tellez, T. The flop. Track and Field Quarterly Review, 1979, 79, 47.

VanEs, B. Should women flop or straddle? Track and Field Quarterly Review, 1979, 79, 42.