A CINEMATOGRAPHIC ANALYSIS OF THE TENNIS SERVE

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

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ORIENTATION TO THE STUDY

Introduction

The serve is one of the most important strokes in the game of tennis today because of the emphasis on the "power" game (Braden, 1977; Brent, 1974; Faulkner, 1970; MacCurdy, 1978; Seixas, 1979; Wilson, 1974). It is the only stroke in tennis in which a player has complete control over the ball; i.e., the ability of the opponent has no effect on the outcome of the service prior to its execution. The serve is important because a player who is always able to win the service can put the opponent on the defensive and, thus, obtain an advantage. Gray (1974) stated that an increasing number of players are utilizing the attacking game; thus, the serve and volley are essential to success.

There is little, if any, disagreement that the serve is a very important aspect of the game of tennis. Even though this is the case, Murphy and Murphy (1975) stated that "new students of tennis . . . find little material in which authors treat the game scientifically. The better known books and periodicals merely describe strokes of top performers without offering a mechanical explanation of why

these players stroke as they do" (p. 23). Murphy and Murphy (1975) stated further:

> New reference material is needed to help inexperienced teachers establish a scientific basis for their tennis teaching. Knowledge of mechanical principles can help teachers distinquish between efficient and inefficient movement, and between correct and incorrect technique. It can enable them to judge the validity of the form they teach and to make allowances for variations in form when necessary. Other things being equal, such a scientific approach is more likely to result in effective teaching than is a system based on the more limited empirical approach. (p. 23)

Beecher (1977) pointed out that numerous books have been written concerning the many aspects of the game of tennis. These are "descriptive guides of individual styles and techniques" that often lack analysis and application of biomechanical principles (p. 1). She stated that the "teacher needs an understanding of the basic biomechanical principles so that a greater degree of success and individual proficiency can be achieved" (p.

2). Beecher (1977) stated further that:

> A study should be made which considers the same variables of this investigation [velocity of forward hip rotation in relationship to the velocity of the served tennis ball], but examines the characteristics of the professional tennis players. (p. 70)

Treadway (1972) recommended the following for further study: (a) cameras operating in excess of 64 frames per second, (b) an overhead camera and an additional side camera, (c) reference points placed on the subject, and (d) appropriate background and subject clothing for belt distinction.

The lack of evidence (Barnaby, 1975; Driver, 1973; Murphy, 1970; Plagenhoef, 1970; Tilmanis, 1975) of such research is further indication that a study was needed in this area. Thus, this study was planned to contribute to the analytical literature concerned with the tennis serve.

Statement of the Problem

The study encompassed an analysis of the acceleration, velocity, displacement, and rotation of various body segments; and the sequence and timing of the joint actions of the subject as a slice/topspin tennis

serve was executed. The subject studied was a female tennis professional on the 1980 professional circuit. She was filmed from overhead, from the side, and from the front. Commands were given to the server to serve to four different areas on the court. Four serves, which were accurate according to each of these commands, were analyzed. A conclusion was drawn regarding the contribution of acceleration, velocity, displacement, angular rotation, and the sequence and timing of joint action to a single successful, accurate, high velocity serve.

Definitions and/or Explanations

For this investigation, the following definitions and/or explanations of terms were established:

Biomechanics: "Mechanics is the study of forces and their effects. The application of these principles to human and animal bodies in movement and at rest, combining engineering with anatomy and physiology, is biomechanics" (Le Veau, 1977, p. 1).

Cinematography: Cinematography is the study of human performance through the use of the motion picture camera (Miller & Nelson, 1973).

Velocity: Le Veau (1977) described velocity as the

"rate of displacement per unit time" (p. 162). It is "a vector quantity having both magnitude and direction" (Northrip, Logan, & McKinney, 1974, p. 52).

Displacement: Le Veau (1977) described displacement as being "the change in position of a body" (p. 159).

Acceleration: Hay (1973) defined acceleration as being the "rate at which the velocity changes with respect to time" (p. 18).

Kinetics: Kinetics refers to "the study of moving bodies, including forces providing motion" (Le Veau, 1977, p. 223). It involves inertia, "that property of a body which makes it resist a change in motion" (Le Veau, 1977, p. 223); mass, " the quantity of matter of which a body is composed" (Hay, 1978, p. 56); and force.

Radian: Hinson (1981) defined a radian as "that portion of a circle which results when the length of its radius is measured along its circumference. The degrees subtended by one radian are 57.3" (p. 282).

Rotational Motion: "Also called angular motion, rotation occurs about a fixed axis" (Le Veau, 1977, p. 163).

Slice/Topspin: The swing is from low to high, sidespin produced from the racquet brushing the backside

of the ball at about a 45 degree angle (Braden, 1977). In a slice serve, the ball is contacted out in front of the body, almost in line with the right shoulder. To hit topspin, the ball is contacted more to the left and slightly back, thus lowering the contact point (Plagenhoef, 1970).

Backswing: This is "the preparation for a stroke in which the racquet is drawn back before being swung forward" (Brown, 1980, p. 11).

Forward Swing: Arm position following the backswing at which point the racquet arm exceeds 180 degrees (Brown, 1980).

Follow-through: Follow-through is "that part of the swinging motion after the ball has been hit" (Brown, 1980, p. 13).

Backscratch Position: The racquet arm is in a position so that the racquet is held over the shoulder, the racquet head pointing toward the ground, and "the upper arm . . . kept high" (Barnaby, 1975, p. 45).

Purpose of the Study

The purpose of this study was to determine, through cinematography, whether a slice/topspin tennis serve was executed by a female professional player according to the

literature. In addition, analytical information was provided that may be helpful to the tennis coach and the teacher.

Questions

The researcher investigated the following questions during the study:

1. How long did the shoulders remain horizontal during the serve?
2. Were the shoulders rotated clockwise before the ball toss?
3. How was the weight shifted before contact?
4. Where was the ball contacted?
5. What was the extent of shoulder and hip rotation before and after ball contact?
6. What was the position of the racquet palm, wrist, elbow, upper arm, and forearm in the backscratch position?
7. Did extensions of knees, elbow, and flexion of wrist occur simultaneously at contact?
8. Was movement sequential: i.e., hip rotation, elbow extension, wrist flexion, and rear foot placement into the court?
9. What was the path of the tossing arm?
10. What was the racquet velocity immediately before

and after ball contact?

11. What was the ball velocity immediately after racquet contact?

Delimitations of the Study

The present study was subject to the following delimitations:

1. The selection of a single female subject who was a tennis professional.

2. Variables of focal distance, light, angle and heights of the cameras.

3. The model of racquet used and the string tension of the racquet.

4. The skill of the subject to perform a slice/topspin serve.

5. The compliance of the balls to the standards of the United States Tennis Asociation.

6. Unlimited warm-up for the subject to become accustomed to the experimental conditions.

7. The type of serve. This was left to the discretion of the server, though it was specified that a flat and a twist serve were not to be executed. It was left to the discretion of the subject to use what she felt was her "best"

execution of the slice/topspin serve. The results will pertain to players attempting that serve.

CHAPTER II

REVIEW OF RELATED LITERATURE

The literature pertaining to the mechanics of the tennis serve encompasses instruction from the stance through the follow-through. However, there is no solid agreement among authors as to the methods of executing the serve. The majority of the references were concerned mainly with the basic serve for beginning and intermediate players.

The slice/topspin serve can be executed with the eastern backhand grip (Barnaby, 1975; Kramer, 1977) or the continental grip (Braden, 1977; Murphy & Murphy, 1975). The stance is generally agreed to be executed (for a right handed player) with the left foot at a 45 degree angle and the right foot parallel to the baseline with the feet shoulder width apart (Barnaby, 1975; Braden, 1977; Faulkner, 1970; MacCurdy, 1978; Plagenhoef, 1970; Seixas, 1979).

In tossing the ball, the palm of the hand is horizontal (Barnaby, 1975; Braden, 1977) and the elbow is extended. The player tosses the ball just above the height of the racquet tip when the racquet arm and body are fully extended. The ball should reach its peak height

at that point so that it appears to "hang" in the air (Barnaby, 1975; Braden, 1977; Murphy & Murphy, 1975; Seixas, 1979; Stockton, 1978). The point of ball contact varies from 1 to 1 1/2 ft. (.30 m to .46 m) diagonally in front of the non-preferred foot (Barnaby, 1975; Kramer, 1977; Seixas, 1979) to 2 ft. (.61 m) in front of the body off the 'hitting' shoulder (Braden, 1977). In contrast to tossing the ball directly in line with the left foot, 'off the hitting shoulder' refers to the technique which the more advanced players employ as they rotate their shoulders backwards, thus causing the tossing arm to ascend vertically to the baseline (Braden, 1977; MacCurdy, 1978; Murphy & Murphy, 1975; Plagenhoef, 1970).

The weight transfer at the beginning of the serve varies according to the body position in the stance. The weight may begin on the back foot (Murphy & Murphy, 1975; Seixas, 1975), evenly distributed on both feet (Braden, 1977), or on the front foot (Kramer, 1977; MacCurdy, 1978). If the weight begins on the front foot, it shifts back as the tossing arm reaches the thigh. The weight transfers forward when the upper arms are parallel to the court (Plagenhoef, 1970).

During the backswing, both hands move downward

together, separate, and then move upward at the same rate (Murphy & Murphy, 1975; Plagenhoef, 1970; Seixas, 1979). Braden (1977) stated that this "down, up, down" motion causes loss of kinetic energy, leaving only the arm to salvage any speed (p. 156).

In the backscratch position, the kneebend, backbend, and shoulder rotation start as the racquet is moving down behind the back (Plagenhoef, 1970). A "high elbow" is important, causing the upper arm to point upward, not forward as when throwing a ball (Plagenhoef, 1970, p. 86).

Plagenhoef (1970) states that there is a relationship between ball speed, racquet head velocity, and striking-mass. The striking-mass is dependent on grip firmness. The formula for determining this relationship is:

$$\underset{\text{ball}}{mV} + \underset{\text{racquet}}{mV} = \underset{\text{ball}}{mV} + \underset{\text{racquet}}{mV}$$

Before Impact = After Impact

(p. 89)

He listed movement variations among good servers that still produce the same amount of success:

> 1) the path of the left arm; 2) the height of the toss; 3) the timing of the weight shift; 4) the racquet path to get in the cocked position;

> 5) the amount of backbend and shoulder rotation; 6) the point at which the ball is struck in relation to both the server and the court; 7) the speed of the whole movement; 8) the timing and use of body segments; 9) the grip and its firmness at impact; and 10) direction and length of the follow-through. (p. 62)

Johnson (1957) studied the relationship between the speed and accuracy of the slice serve with movements used in serving. Ten advanced female tennis players of a national or a southern California 1954 sectional ranking in singles were selected as subjects. An 8 mm camera, mounted on a tripod, was placed 28 ft. (8.5 m) from the serving area. A recently calibrated stopwatch, operated by a skilled operator, was used to determine the ball velocity. A Recordak film reader was used to analyze one frame of the film at a time.

No relationship was found between the speed and accuracy of the serves; the two were independent factors. The players were ranked according to the combined total of their velocity and accuracy scores. Johnson noted that the six subjects who placed more emphasis on velocity than accuracy were ranked within the top seven of the combined

rankings. The highest skilled subjects were able to serve at higher rates of speed while maintaining average accuracy, thus giving approximately equal emphasis to speed and accuracy.

The author concluded that differences noted in the grip, the degree of body rotation and backward bend, and the extension of the arm at impact all appeared to be highly related to success in serving. The highest ranked subjects had more body rotation and backward bend. Arm extension at impact was emphasized. Those subjects using the continental grip were ranked higher than those using the eastern forehand.

Plagenhoef (1971) compared the serves of two professional players, Ken Rosewall and Rod Laver. He outlined three procedures:

1. Locate center of gravity and determine the moment of inertia of combined hand-racquet segments.
2. Determine the force of impact transmitted to the hand through the racquet due to the ball impact.
3. Analyze the arm and leg outside of the link system [force from the front foot, up the

> leg, across the hip joints, and up through the racquet arm, not including the back leg and the ball toss arm] separately, and the applied force obtained to the link system at the appropriate joints. (p. 138)

Plagenhoef (1971) found that the hand and racquet decelerated slightly before impact, giving evidence that preparation was made in anticipation of impact. Absolute maximum deceleration of a body segment facilitated increased velocity of the next segment. Laver and Rosewall maximally decelerated the shank early. Laver differed from Rosewall in that the thigh, trunk, upper arm, and forearm decelerated in sequence before impact, causing his trunk to be the most influential segment in movement prior to contact. Rosewall's legs and hands were his most influential segments before impact.

The leg and hip moments of force before impact were the same for both players. Rosewall used more muscular force for upper arm and elbow extension; and Laver used more muscular force for hand flexion. Rosewall's stopping action during follow-through was more abrupt, resulting in greater moments of force at all joints. Laver's sequence of action between the body segments produced a faster ball

velocity with less muscular effort.

Treadway (1972) performed a descriptive analysis of the tennis serve which focused on the magnitude, direction, speed, and sequence and timing of the joint actions; the ball velocity immediately after contact of the ball was also studied. Two 16 mm Bell and Howell cameras with black and white film were used to film the subjects. The cameras were set at 90 degrees to each other; one to the front and the other to the side. A multidimensional clock for synchronizing front and side film views was calibrated to revolve 60 times per minute. Two body belts, equipped with frontal plates and a dorsal projection, were used for measuring spinal and pelvic rotation. The subjects were male, ranging in ages from 18-21 years, having had tennis experience since 5 to 9 years of age.

For analysis, emphasis was placed on the description of the force development phase. From the results of the analysis, the author stated the following:

1. Placement of the left foot ranged from almost parallel to nearly perpendicular to the baseline.

2. The toss was consistently in front of and to the right of the players. It was in excess of the

height of the extended arm and racquet.

3. The position of the metatarsophalangeal joints at contact ranged between zero degrees and 65 degrees of flexion. Movements in the joints were characterized mainly by flexion, and in some cases, were followed by extension.

4. Angular changes in the knee joint of the left leg indicated that the extension of the knee was greater before contact. None of the subjects had a fully extended knee at contact.

5. Movement in the hips and the spine was primarily rotational. However, in some trials backward rotation preceded the forward rotation.

6. During elbow extension, the upper arm was medially rotated and elevated from the shoulder.

7. The wrist hyperextended and then flexed before ball contact, a range of 70 to 40 degrees. At contact, the angle varied between 37 degrees of hyperextension to 8 degrees flexion.

8. The ball was always contacted forward and to the right of the subject, being struck after it began falling. At contact, each subject had laterally tilted his trunk to the left.

9. The legs were the first to act, followed by the hips and spine, shoulder, elbow, and wrist.

Treadway concluded that:

1. The patterns of serving . . . closely follow the general descriptions as presented by the coaches and professional players.
2. The sequence of joint actions was similar to the descriptions of the overhand throwing pattern and the tennis serving pattern as presented by kinesiologists in the reviewed literature.
3. The main similarities noted in the movement patterns were those of the wrist and elbow of the racquet arm and the sequence of the action.
4. Differences were found in the movement patterns associated with the metatarsal, ankle, knee joint of the left leg, and the hips and spine. (p. 84)

Beecher (1977) investigated three components of the flat tennis serve. These were: (a) velocity of the served tennis balls, (b) mechanical involvement of the hips, and (c) the strength levels of the arm, wrist, and shoulder. The primary purpose of the study was to determine if a

statistically significant relationship existed between ball velocity and the variables of hip rotation, and/or composite arm, wrist, and shoulder strength.

A two camera set-up was used to determine the kinematic data for the tennis ball service velocity and the total body service motion. Camera one, used to determine ball velocity, was a Visual Instrumentation Corporation Cine-5 (model SP-1) with Sony F 1.2 zoom lens. The frame rate was 100 frames per second with an exposure time of 1/400 of a second. The camera was at a 90 degree angle to the expected line of ball trajectory. Camera two was a GAF (model ST-602) Super 8 motion picture camera. The frame rate was 50 frames per second with an exposure time of 1/100 of a second. It was positioned above the subject in order to obtain the occurrence of motion in the hips. For each subject's highest ball velocity trial from camera one, the corresponding trial from camera 2 was analyzed to determine the velocity and magnitude of forward hip rotation.

The hypothesis of no significant relationship between the magnitude of forward hip rotation and ball velocity of the flat served tennis ball was accepted. A significant relationship existed between the velocity of hip rotation

and ball velocity, and between composite static arm, wrist, and shoulder strength to ball velocity. A significant relationship was found between the variables of forward hip rotation and velocity of smaller linked body segments, thus maintaining the conservation of momentum.

CHAPTER III

METHODS AND PROCEDURES

Preliminary Procedures

The investigator surveyed, studied, and assimilated information from documentary sources which were related to the present study. The tentative outline was formulated, revised, and filed as a prospectus in the Office of the Provost of the Graduate School. Approval was secured from the Human Subjects Review Committee of Texas Woman's University to conduct the study.

Selection of Instruments

The three cameras used for filming were high-precision equipment: two of the cameras were set at 500 frames per second (fps) so as to eliminate blurring. The third camera was spring driven and was set to film at 60 fps. The cameras were property of the Texas Woman's University's Biomechanics Laboratory and were found to have acceptable accuracy and reliability.

The side camera was 16mm-1PL manufactured by Photo Sonics, Burbank, California and was set to film at a rate of 500 frames per second. The front camera, set at 60 fps, was a Bell and Howell 70-DR, manufactured by Bell and

Howell. The overhead camera, set at 500 fps, was a Locam (model 51), manufactured by the Redlake Corporation, Santa Clara, California.

Kodak black and white Tri-X Reversal Film, perforated on both edges, was used for filming. Outdoor ASA 200 was used to provide the best compromise between speed, grain, size, and resolution.

Selection of the Subject

Written consent for filming was obtained from the subject, Anne Smith, a female professional on the 1980 professional circuit. She was ranked 23rd in the world at the time of the filming and won the 1980 Wimbledon women's doubles one month after filming.

Description of Equipment

For the filming, a two-tier painter's scaffold was erected. The scaffold had locking wheels for ease in mobility and security. It was anchored at the top to the tennis fence for stability.

A diving board, 6'3" X 3" X 6" (1.9 m X .08 m X .15 m), was constructed and secured to the top of the scaffold to support and house the Locam camera. A wooden box, in which the camera body laid, was nailed to the end of the diving board and a hammock was wrapped around the camera

as a precaution against camera slippage from the tripod. The tripod and hammock were strapped onto the board in two areas.

A plywood board was constructed and placed in front of the Bell and Howell 70-DR camera. The board was positioned so as to protect the camera lens from possible damage from served tennis balls (see Figure 1).

A diagram of the belt used for measuring hip rotation of the subject appears in Figure 2. This belt, with a dorsal projection, was worn around the waist so as to be of no hindrance to the subject's serving motion.

The cameras were at right angles to each other. The overhead Locam camera lens was 12'1" (3.68 m) from the ground and placed directly above the subject. The lens of the 16 mm - 1PL was 47'2" (14.4 m) from the subject and 4'6" (1.4 m) from the ground. The Bell and Howell 70-Dr camera lens was 40' (12.2 m) from the subject and 4'6" (1.4 m) from the ground.

The origin for the three cameras was 22 1/8 in. (.56 m) high. It was placed diagonally 4'7" (1.4 m) from the inside of the center mark and 2'7" (.79 m) from the inside of the baseline. A reference box was constructed to hold trial sheets. The sheets were visible to all three

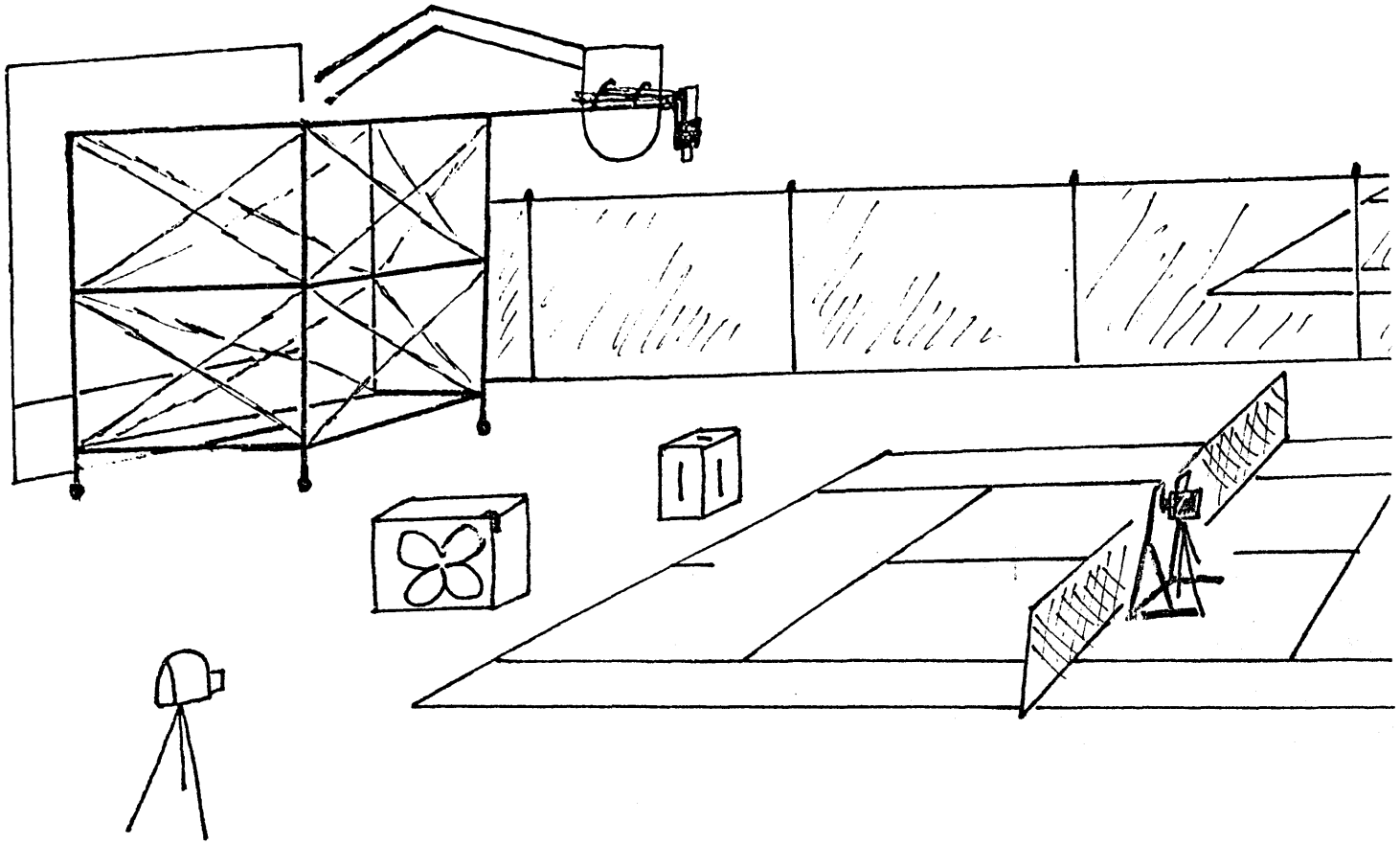

Figure 1. Filming location.

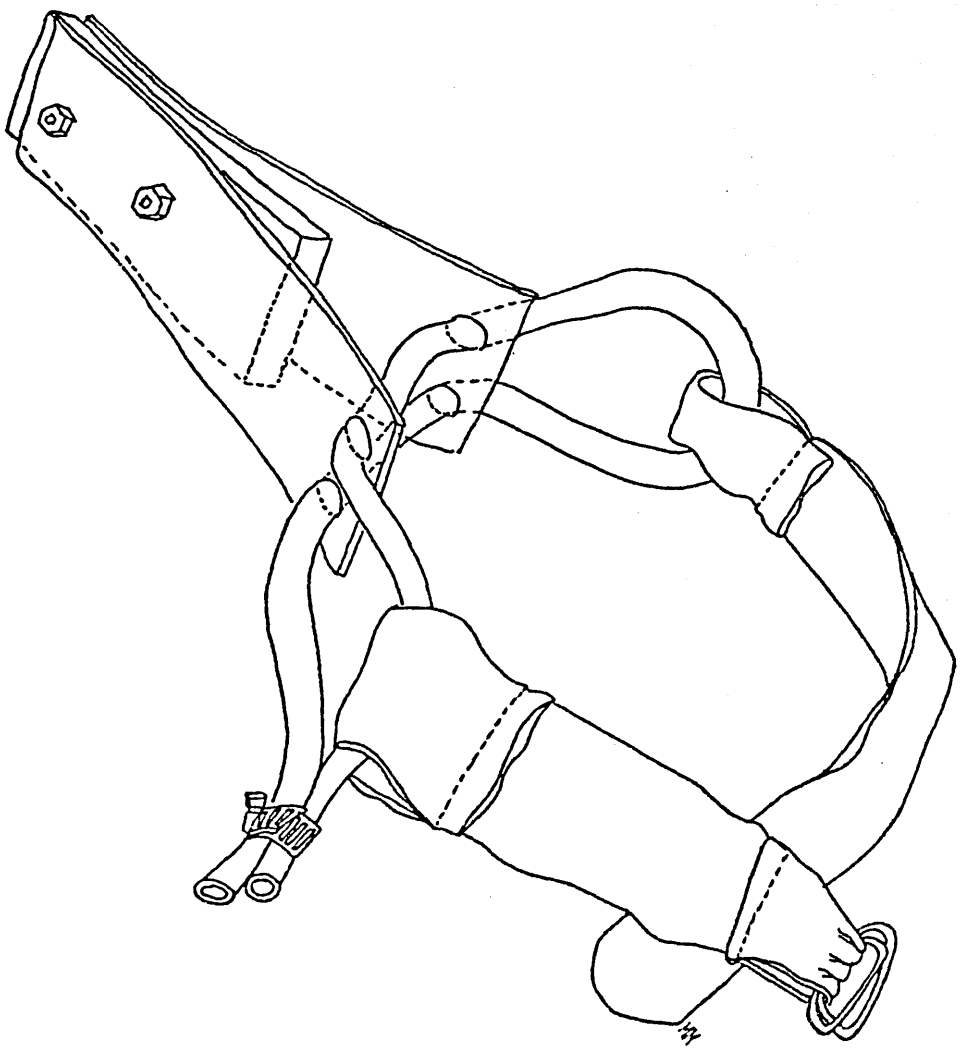

Figure 2. Hip belt.

cameras.

The scaffold and diving board were not safe enough to hold a person and maintain camera stability. A General Telephone Electrical (GTE) repair bucket truck, with a 32 foot (9.8 m) extension, was parked outside the tennis court fence. The overhead cameraman was in the bucket at a level with the diving board as he leaned over for focusing. Because of a slight limitation in the reach of the GTE bucket truck, the subject stood approximately 2 ft. (.61 m) behind the baseline.

Collection of Data

The filming took place on the morning of May 2, 1980, at the tennis courts at Texas Woman's University in Denton, Texas. Assistants were present to aid in the collection of data. Three assistants operated the three cameras, one collected tennis balls, and one assistant recorded the service location and whether the serve was good or a fault.

The subject was given unlimited warm-up in hitting groundstrokes and in serving. When ready, she was given the instructions as to where to serve the ball. These were: short forehand, long forehand, center of the service court, and long backhand (as viewed by a

right-handed returner). The command, "Ready, (pause) Go," was given so as to synchronize the subject's service with the assistants' operation of the cameras.

Treatment of Data

Four serves that best exemplified the commands, i.e., those striking the court in the proper location and those closest to the service box lines, were chosen for analysis. A separate data file was created for the front and side views through the use of a cathode ray terminal interfaced with an Electronics Graphics Calculator manufactured by Numonic Co., Lansdale, Pennsylvania. The Texas Woman's University computer was a DEC-system 2050, manufactured by Digital Equipment Corporation. A time interval that coincided with both films was determined according to the speeds of the individual cameras.

After digitizing the first serve, it was found that the camera speeds were not consistent. The side camera had reached a rate of only 300 fps because insufficient time was allowed for the camera to attain maximum speed before filming. Serve number 12 was found to have the highest camera speed. The film speed of the front camera was accurate at 60 fps. For both views, the number of frames was counted for the following sections: (a) the

beginning of the serve to the ball toss, (b) the ball contact, and (c) ball contact to right foot contact. The time intervals between these sections were determined for the front view by dividing the number of frames by .017. The following formula was then used to determine the frames per second for the side camera, and thus the frame number to be digitized.

$$\frac{\text{\# frames for side section}}{\text{time interval, front camera}} = \text{correct fps for side camera} \quad (1)$$

The front view film was digitized every 2 frames. The side view was digitized every 10 frames from the beginning of the serve to the ball toss, every 16 frames from the toss to ball contact, and every 12 frames from ball contact to foot contact (see Table 1).

The two data files were treated by three computer programs. The first two programs, Dig2c and Knmtc2, adapted by Luke Kelly, a graduate assistant at Texas Woman's University, combined the front and side views producing three link systems and calculated segment angles and segment lengths. The first link was the left foot, shank, thigh, the hip, right thigh, shank, and foot. The second link was the left foot, shank, thigh, trunk, left upper arm, forearm, and hand. The third link was the left

Table 1

Determination of Frame Number for Digitizing

Front Camera (Bell & Howell)	Number of Frames	Time (sec.)	Frames Digitized
start to toss	30	.5	
	> 44	> .73	2 frames
toss to contact	74	1.23	------- =.033
	> 9	>.15	60 sec.
ball contact to foot contact	83	1.38	
Side Camera (16mm-1PL)	**Number of Frames**	**Frames per second**	**Frames Digitized**
start to toss	153	306	10/306 = .033
	> 353	> 484	16/484 = .033
toss to contact	506	411	
	> 56	> 373	12/373 = .033
ball contact to foot contact	562	406	

foot, shank, thigh, trunk, shoulders, right upper arm, forearm, and racquet. These links were treated by the program, Kincor, written by Luke Kelly. This program rearranged the output so that it was suitable for use by the Lamb program, adapted by Luke Kelly from Plagenhoef's program (1971). The Maklnk program, written by Programmer Analyst Debra Odom at Texas Woman's University, combined the previous lamb output files and the input file for link 3, producing a file that was executed by Lamb for the

final output, Lamb.4. Lamb.4 produced data for velocity, acceleration, angles, and smoothed angles for the segments of link 3.

The following procedures were used to answer the hypotheses of the study:

1. To determine how long the shoulders remained horizontal during the serve, the front and side views of the shoulders and racquet arm were traced. The time was determined by counting the number of frames and multiplying by the time elapsed between designated frames. The Lamb.4 output was utilized as a comparison to the tracings. A plus or minus 10 degree deviation from 180 degrees was allowed by the investigator because a human subject will deviate from the 180 degree horizontal as the rotation of the upper arm may cause rotation of the spine but no lateral flexion of the spine.

2. To determine if the shoulders rotated clockwise before the ball toss, the top view film was used for tracing.

3. An entire tracing of the serve was used to determine the weight shift before ball contact. The link 3 segment velocities and accelerations

were plotted, using a Hewlett-Packard 9810 Calculator computer interfaced with a 9862 A Plotter. The graphs were compared and analyzed.

4. The front and side views were used to determine the position of ball contact in relationship to the amount of shoulder flexion and abduction.

5. The extent of shoulder and hip rotation was determined from the top view filming. The degree of shoulder rotation was determined by bisecting the vertical axis with each frame's tracing and measuring the angle from the first frame to the last frame of rotation. The belt was traced to determine the hip rotation.

6. The position of the palm, wrist, elbow, and upper arm of the racquet arm in the backscratch position were traced from the front, top, and side views.

7. The sequence of extension of the knees, elbow, and flexion of the wrist at contact were determined from the Lamb.4 output and from tracing the front and side views.

8. The sequence of movements during the serve was determined from the front and side view

tracings.

9. The racquet velocity before and after contact was determined from tracing the two frames before and after contact. The displacement was determined by subtracting the change of the racquet's position before contact, at contact, and the frame after contact. Velocity was determined using the following formula:

$$V = \frac{\text{displacement}}{\text{time}} \qquad (2)$$

(Gowitzke, 1979, p. 48)

10. The ball velocity was determined by finding the distance traveled by the ball over two frames after contact and dividing that by the time interval involved (see Equation 2).

11. The path of the tossing arm was traced using the front, top, and side views.

Preparation of Final Written Report

The data were organized and presented in appropriate tables and figures. The data were summarized and conclusions were drawn.

The investigator prepared, submitted, and revised the report in accordance with the suggestions of the members

of the thesis committee. A final written report included recommendations for further studies.

CHAPTER IV

PRESENTATION OF THE FINDINGS

In Chapter IV, a description of the subject's tennis serve is presented utilizing various frames which coincide with those digitized for the Lamb program. The answers to the questions which appear in Chapter I are within this description.

Initially, the investigator wished to analyze the different variables used in directing the ball to the four positions on the court, previously described. However, the use of the top view was limited by the fact that the cameraman inadvertently failed to include the wrist and racquet within the focal view.

Description of the Tennis Serve

In Frame 1 of the serve, the left foot (the foot nearer the net) was nearly perpendicular to the baseline, and the heel was in line with the instep of the right foot (see Figure 3). The right foot was parallel to the baseline. The feet were slightly more than shoulder width apart, and the weight was on the left foot. The weight remained forward as the subject bounced the ball, and the racquet arm was behind the right leg. The racquet arm was alternately flexed and extended as the ball was bounced

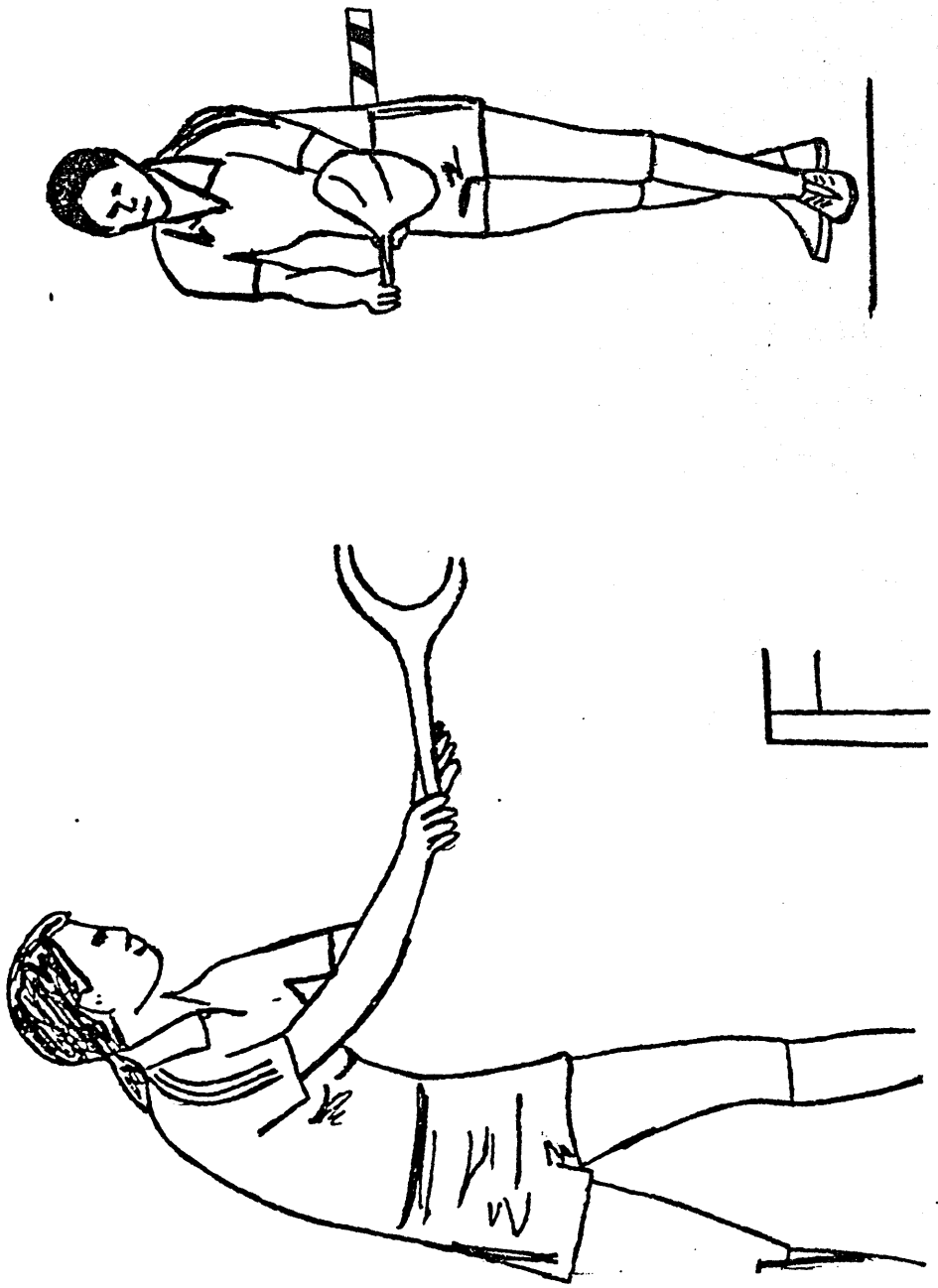

Figure 3. Frame 1.

and caught. As the arms were raised upward, the weight moved slightly backward but remained predominately on the front foot. The racquet face was perpendicular to the baseline, and the shaft of the racquet rested on the left hand. The hips faced the right net post, and the spine was flexed and rotated to the left. The racquet and arms were, thus, positioned to point toward the net.

During the next four frames, the left thigh inwardly rotated as the spine rotated to the right. The weight remained on the front foot. There was extension of the upper arms as they moved toward the court together. The elbow of the tossing arm was extending as the elbow of the racquet arm was flexed. The ball was held on the fingertips of the first four fingers (see Figure 4).

In Frame 8, there was spinal rotation to the left and lessened flexion (see Figure 5). The hips maintained their position toward the net post but the weight was moved to a location over both feet. The racquet face was still perpendicular to the court and the top of the racquet was rotating outward with the right arm. The arms had separated and both were extended.

The tossing arm flexed upward after a clockwise movement (see Figure 6). The arm movement nearly

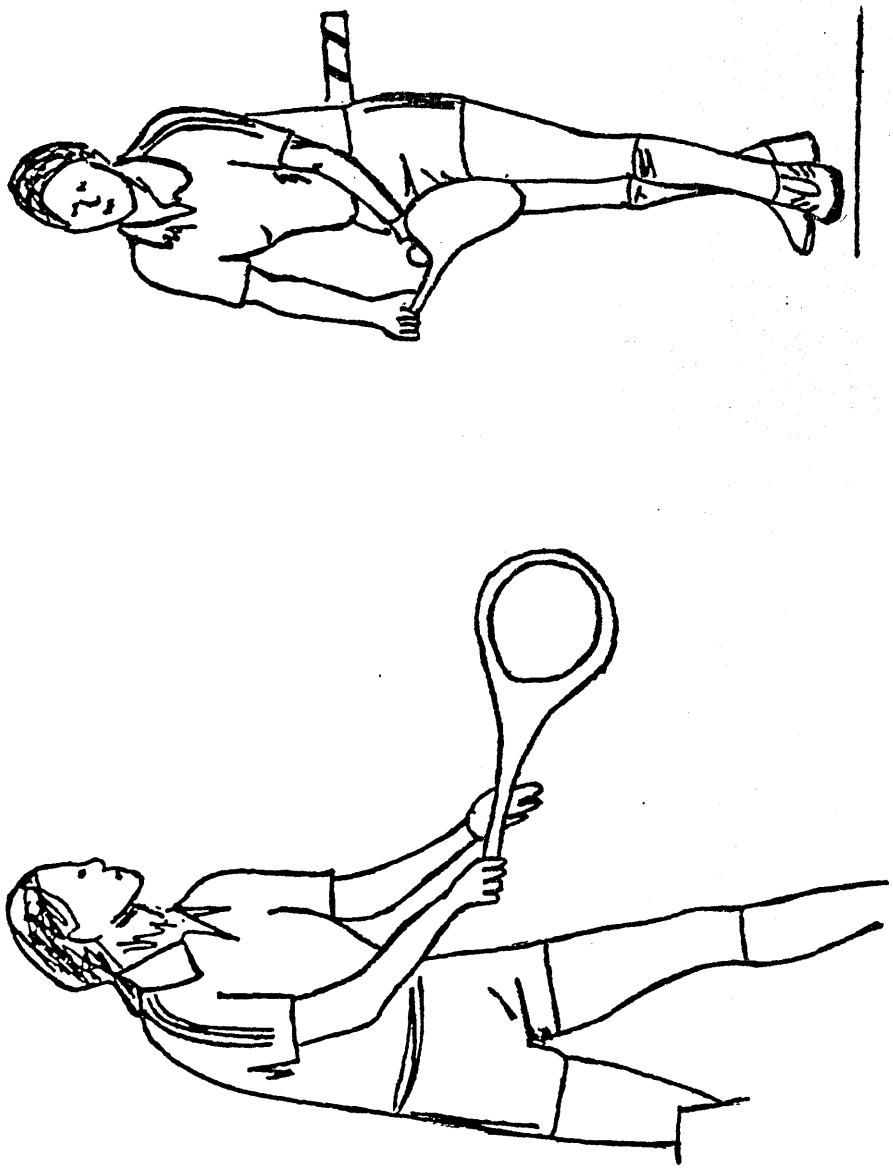

Figure 4. Frame 5 and Position 4 of Figure 37.

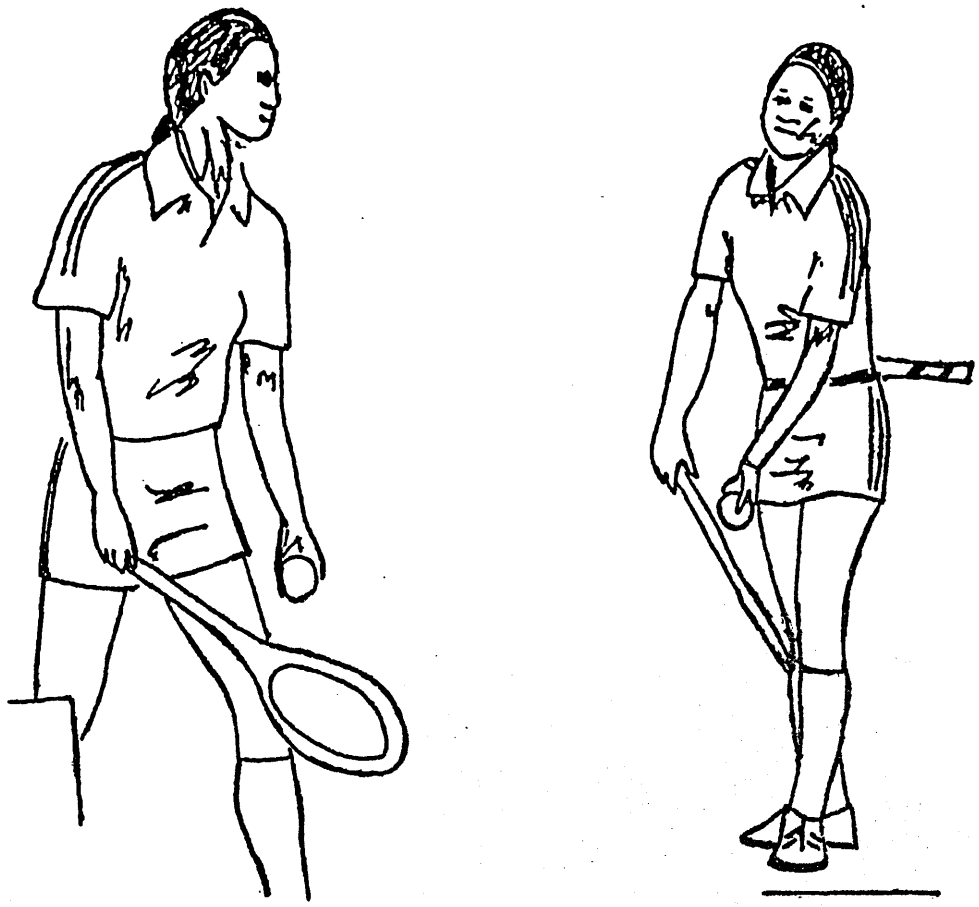

Figure 5. Frame 8 and Position 5 of Figure 37.

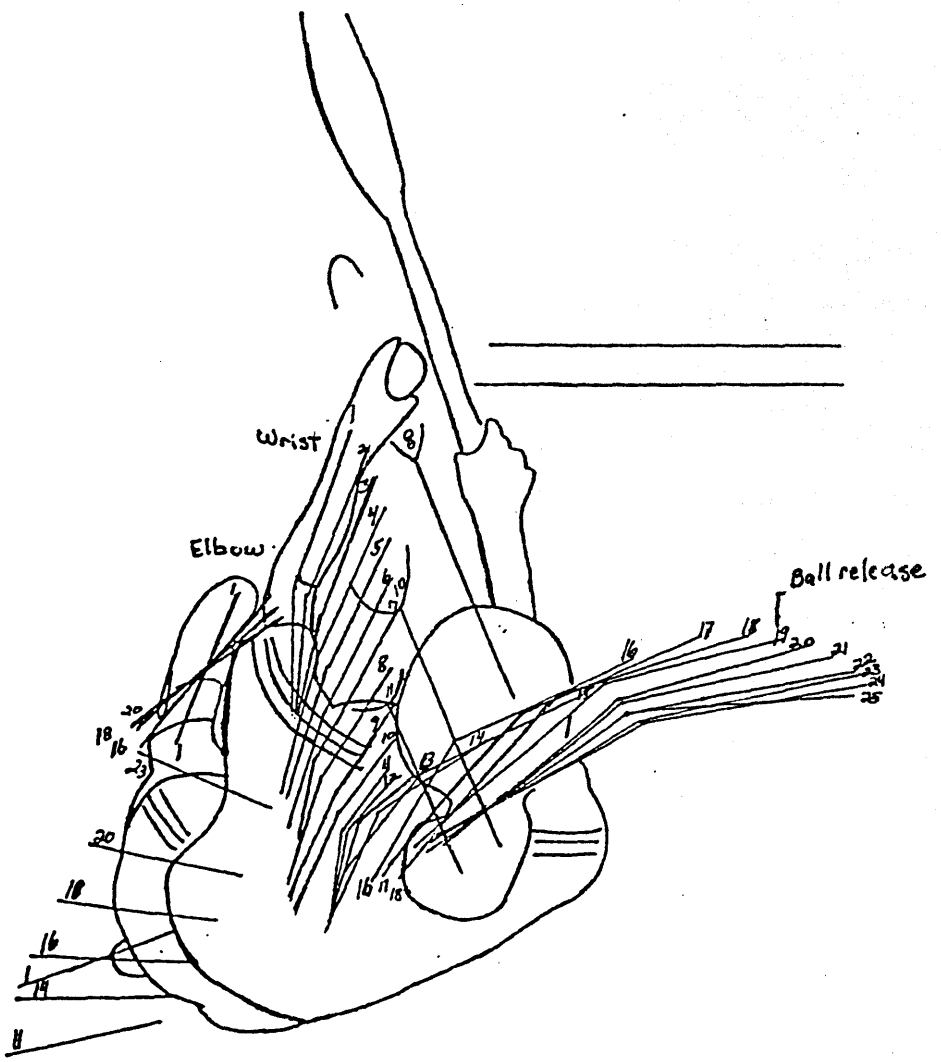

Figure 6. Tossing arm motion.

coincided with the rotation of the shoulders and spine. The shoulders rotated 62 degrees and the tossing arm rotated 55 degrees.

If the tossing arm were to rotate fully with the trunk, the ball would be released in the sagittal plane in line with the left shoulder rather than to its side. A toss in the sagittal plane would not allow the player to reach toward the net to contact the ball.

Figure 7 indicates that the tossing arm remained stationary at Position 10 while the racquet arm continued to move toward the back fence. This allowed the arms to rise during the same time period. There was a greater increase in velocity of the tossing arm because of the greater distance traveled by the tossing arm as it moved upward and flexed (see figures 7 and 8). The elbow of the tossing arm was not fully extended at ball release and the hand was slightly supinated. Figure 9 is further indication of the final position of the tossing arm and the hand. The arm was positioned upward in line with the left thigh. The left foot had moved to a 45 degree angle, pointing toward the right net post (see Figure 6).

In frames 11, 13, and 15, the tossing arm continued to move upwards (see figures 10, 11, and 12). The left

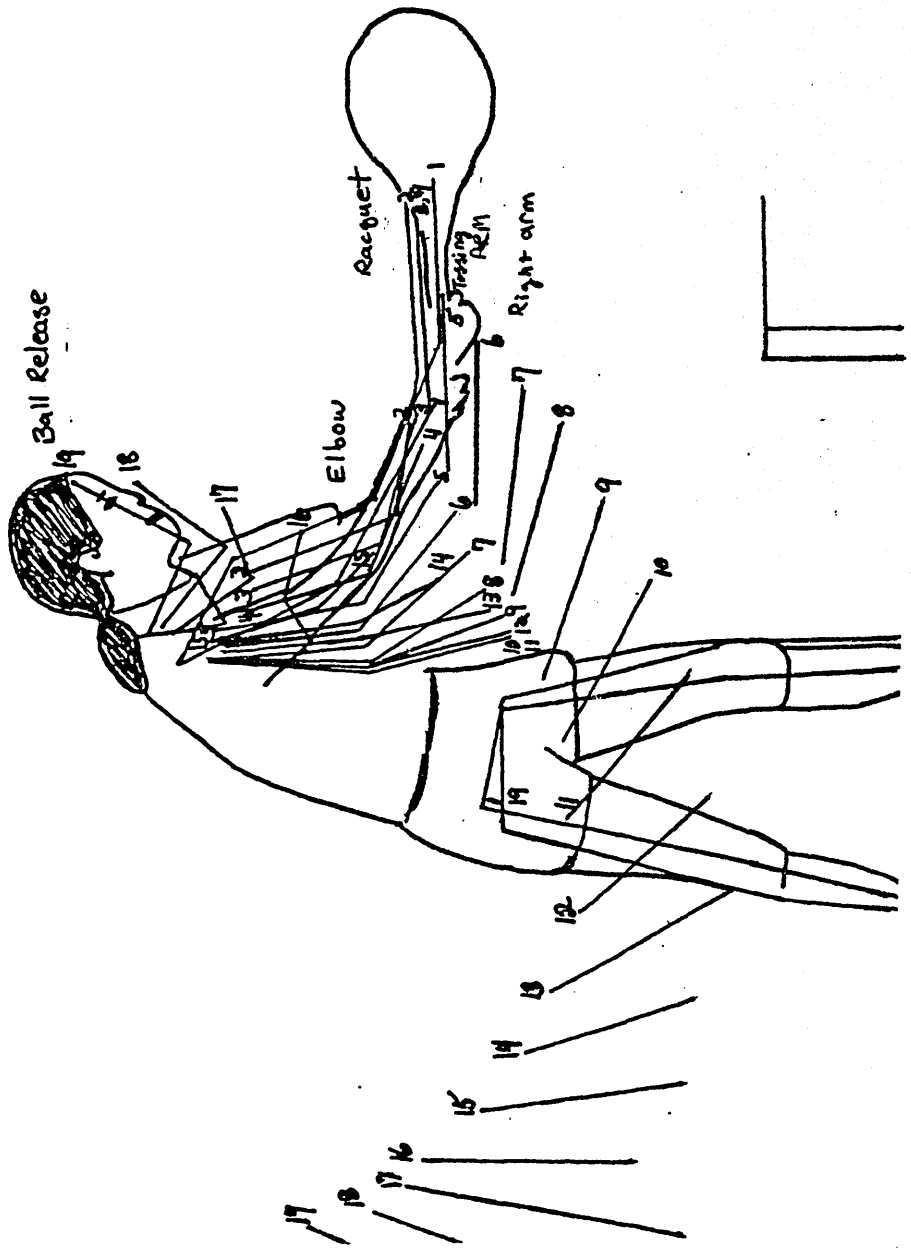

Figure 7. Tossing arm and racquet arm motion.

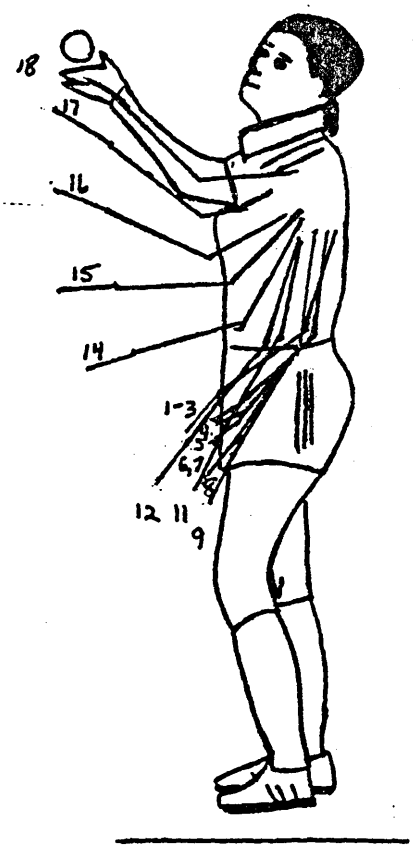

Figure 8. Tossing arm.

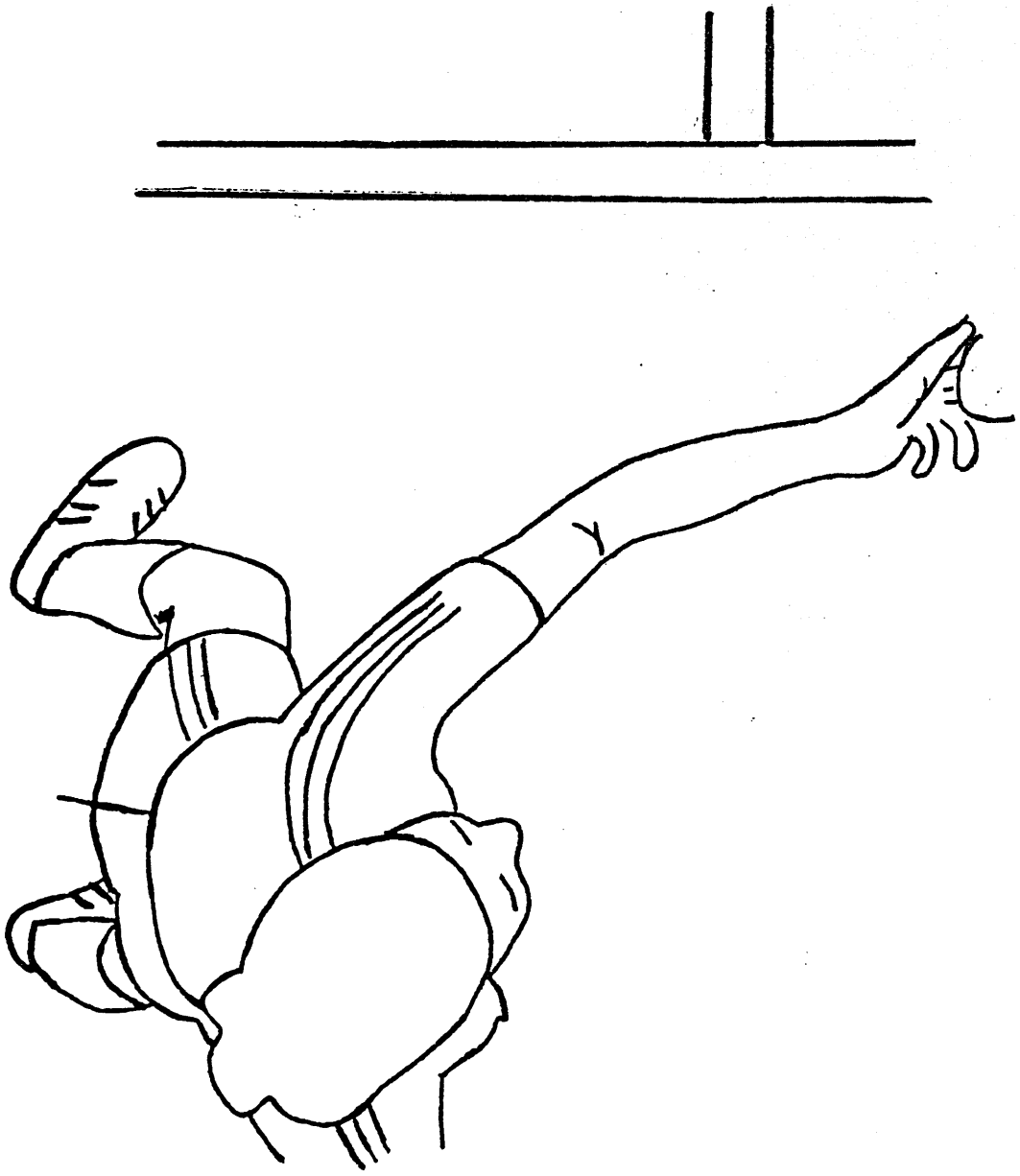

Figure 9. Tossing arm at ball release.

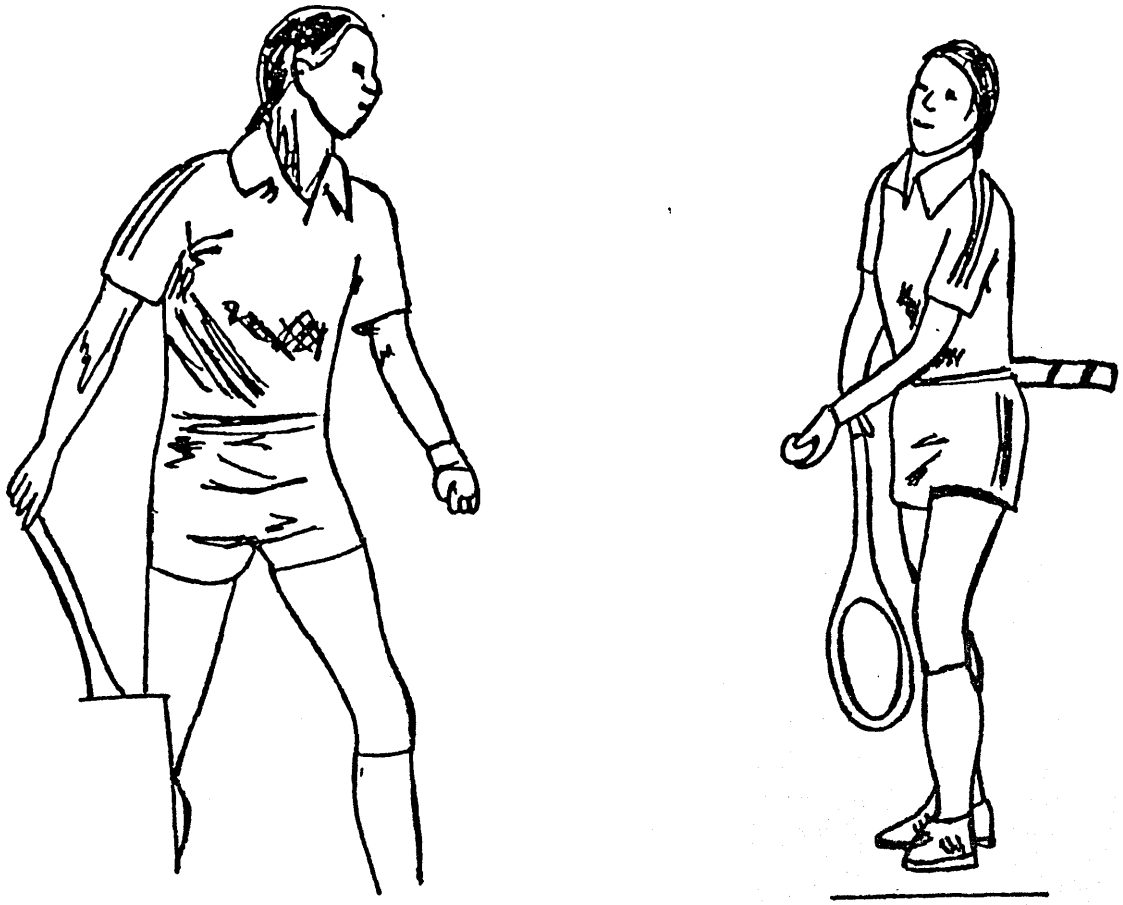

Figure 10. Frame 11 and Position 7 of Figure 37.

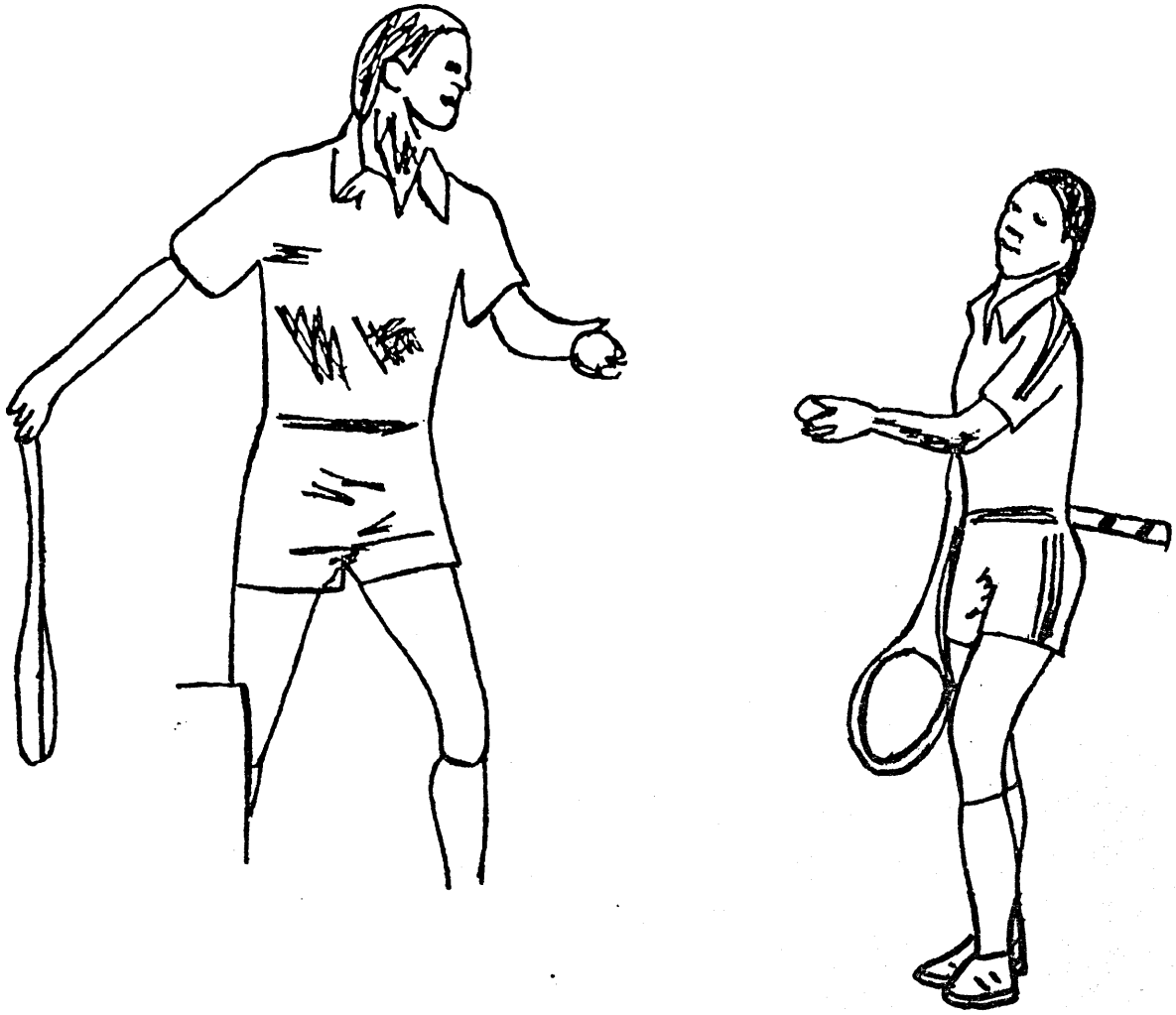

Figure 11. Frame 13 and Position 8 of Figure 37.

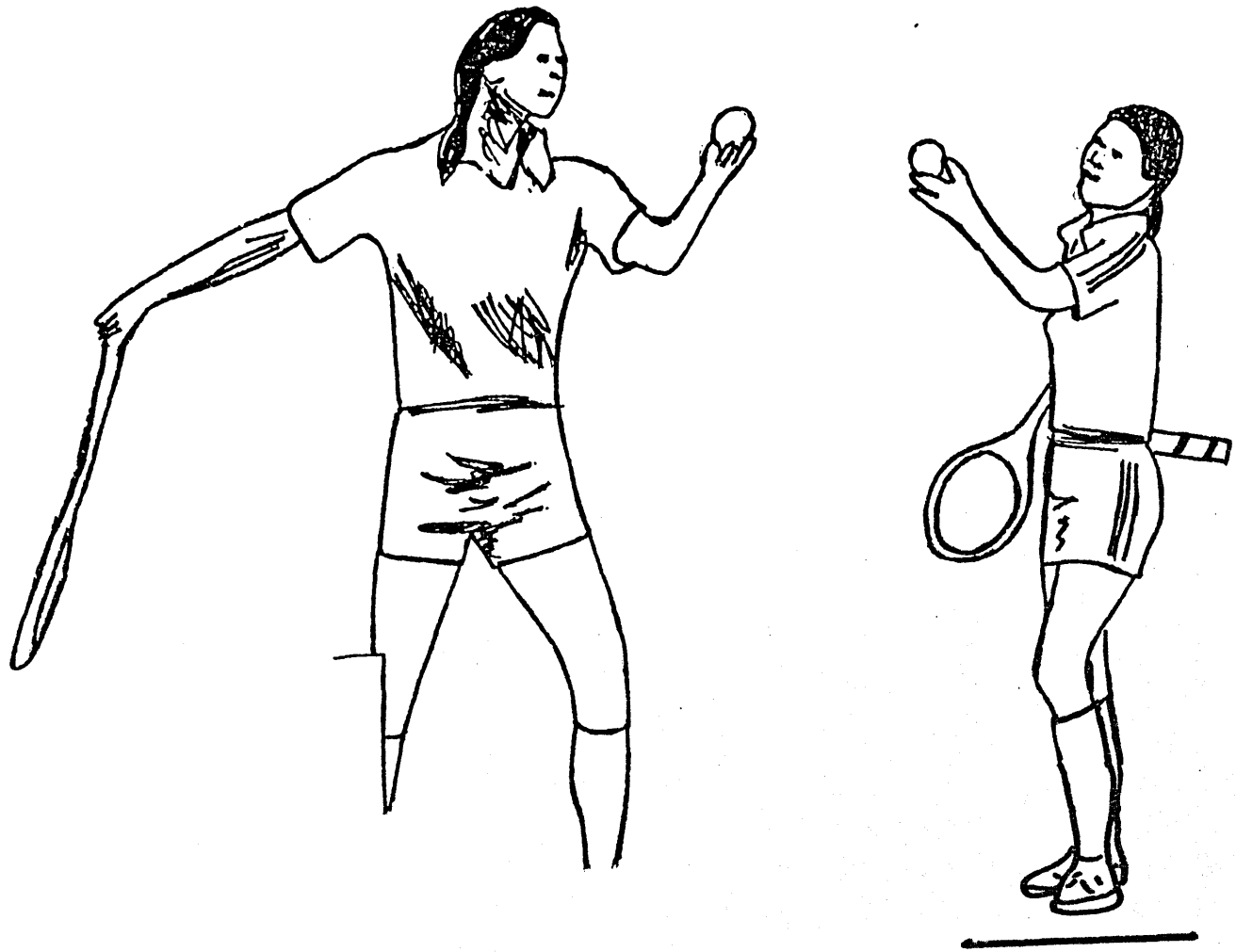

Figure 12. Frame 15 and Position 9 of Figure 37.

foot was inverting as the thigh inwardly rotated. The weight was slightly forward, and the knees were flexing. In Frame 13, the racquet face was held parallel to the net and continued to be outwardly rotated. In Frame 15, the ball was released; the upper arm of the racquet arm was almost parallel to the court, and the hips were nearly perpendicular to the net.

In Frame 18, the hips were perpendicular to the net as the knees were flexing. The left toe was almost pointing toward the sideline as both feet began to plantar flex. The right hip was inwardly rotated causing the thigh to adduct. The tossing arm continued moving upward and the racquet arm was parallel to the ground. The racquet was moved upward as the palm supinated. The weight continued to be moved forward toward the net as the knees flexed. The subject watched the ball rise and continued to do so through Frame 38. There was no lateral flexion or flexion of the spine at this position (see Figure 13).

Frames 21, 25, 27, and 29 showed that the racquet arm moved toward the "backscratch" position as the knees continued to flex (see figures 14 - 17). In Frame 21, the upper arm of the racquet arm was parallel to the court as

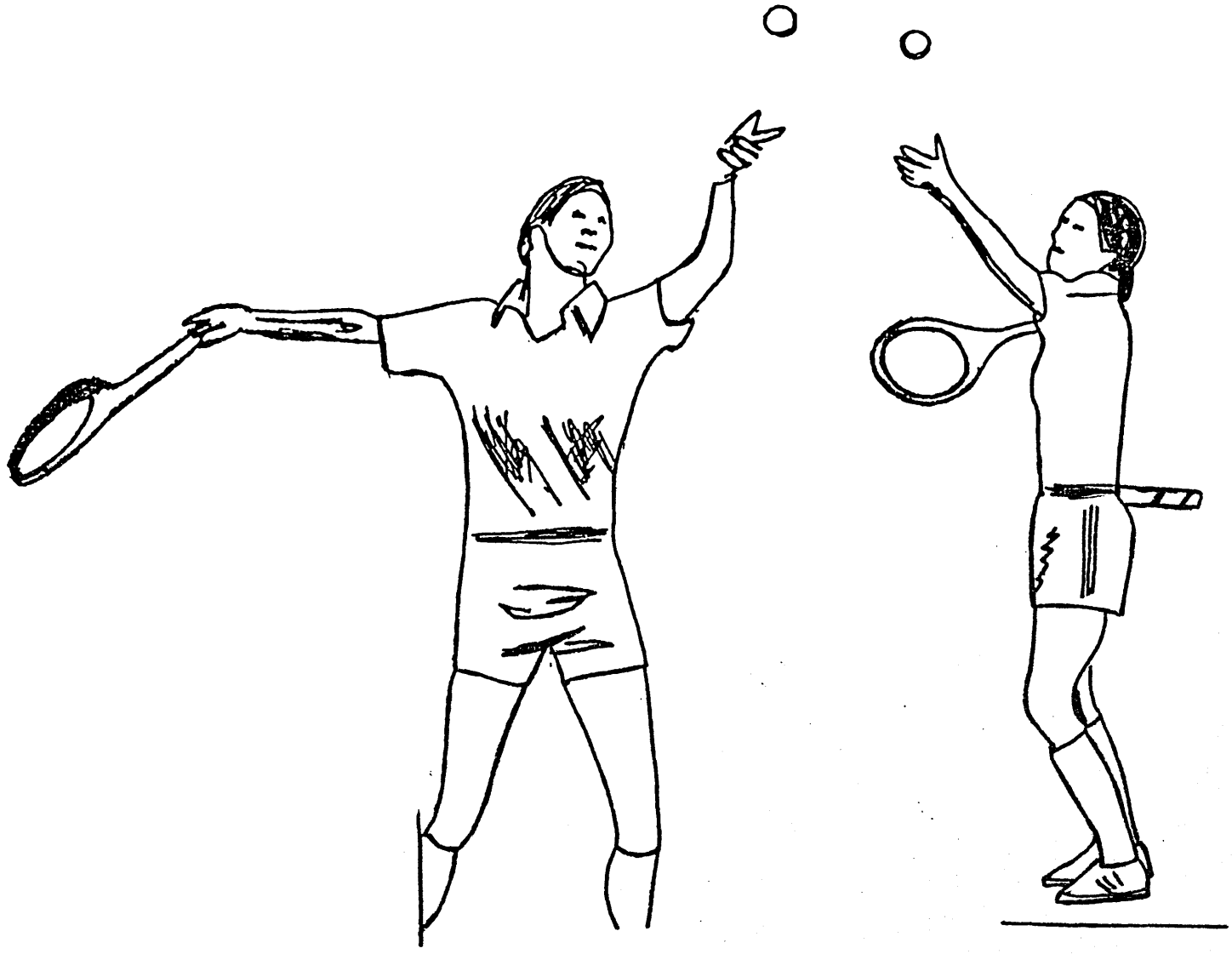

Figure 13. Frame 18 and Position 11 of Figure 37.

Figure 14. Frame 21 and Position 14 of Figure 37.

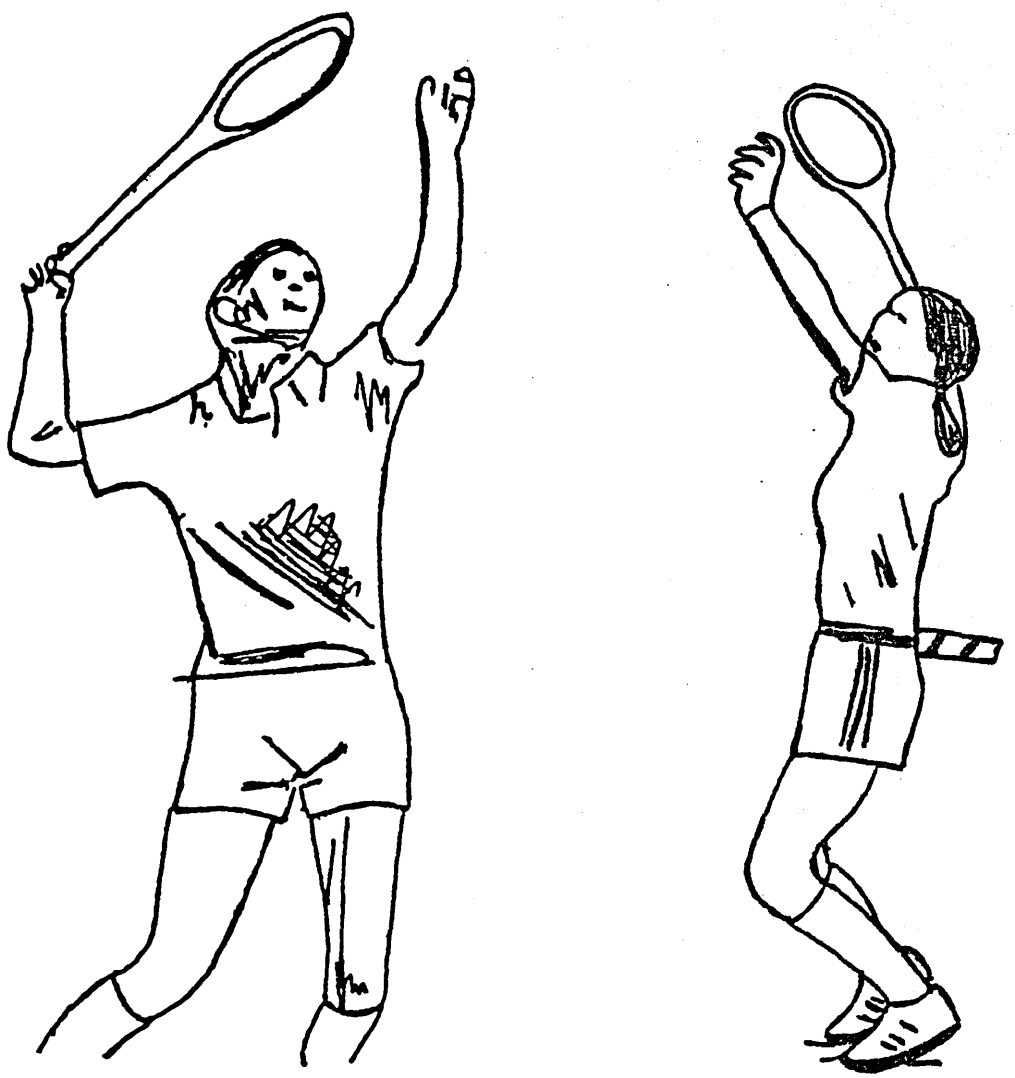

Figure 15. Frame 25 and Position 17 of Figure 37.

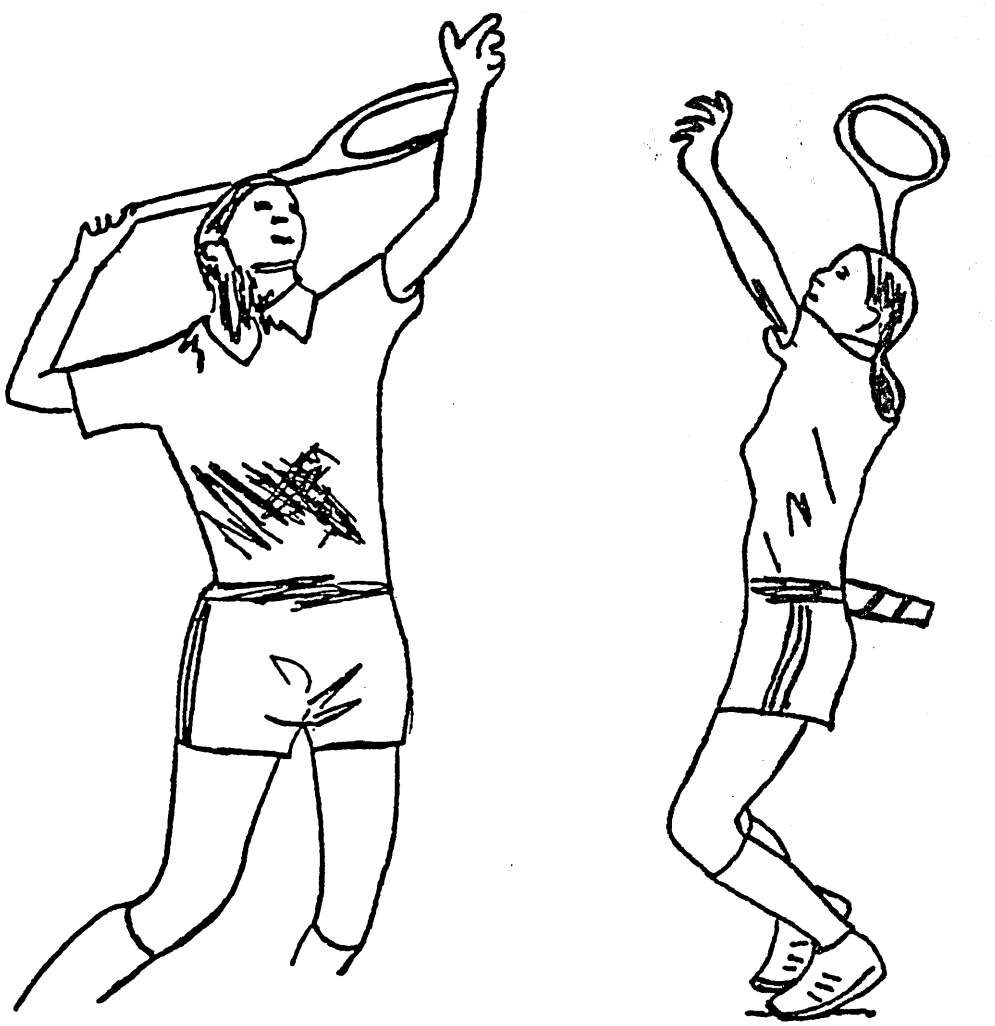

Figure 16. Frame 27 and Position 18 of Figure 37.

Figure 17. Frame 29 and Position 20 of Figure 37.

it outwardly rotated, and the forearm continued to flex. The spine was very slightly hyperextended. The right heel was off the court, and the thighs were shoulder width apart. The racquet face was becoming parallel to the court and continued to do so through Frame 27. In Frame 25, both heels were off the court as the knees continued to flex. The hips were leading toward the net causing lateral flexion of the spine to the right. The tossing arm began to extend. In Frame 27, the racquet passed over the head because of more hyperextension and ipsilateral rotation of the spine. In Frame 29, the racquet was positioned behind the subject's head, and the racquet face was almost parallel to the back of the subject's head. The knees began to extend.

As shown by the tracings in Figure 18, the shoulders were approximately horizontal in frames 1-30. The positions on the tracing were taken every 15 frames; the time span was 1.164 seconds.

During positions 6-8 (the arms are absent from the drawing), the racquet and tossing arm were separating. In Position 11, the upper arms were nearly parallel to the court, and the ball release occurred during the tenth frame of the twelfth position. In Position 17, the upper

arm of the racquet arm was outwardly rotating, causing the shoulders to appear non-horizontal. The racquet was moving over the head at Position 25 and was in the backscratch position during Position 29 (see Figure 18). Figure 19 shows the front view of the shoulders.

The results of the Lamb.4 output showed that the shoulders were horizontal in frames 1-33. Frame 33 showed the "backscratch" position. This time span was 1.089 seconds, a difference of 0.075 seconds between the computer output and the tracing (see Table 2).

In Frame 32, the subject was nearly in the "backscratch" position (see Figure 20). Both knees had begun extension, and the right hip was inwardly rotated as the left hip outwardly rotated. The spine was hyperextended and rotated to the right. The feet were shoulder width apart.

In the "backscratch" position, (Frame 33, see Figure 21), the palm of the racquet hand and the racquet face were parallel to the net (see Figure 22). The wrist was not deviated but was slightly hyperextended. The elbow was flexed to 55 degrees, and the forearm was parallel to the court. The upper arm was also parallel to the court with the glenohumeral joint outwardly rotated and

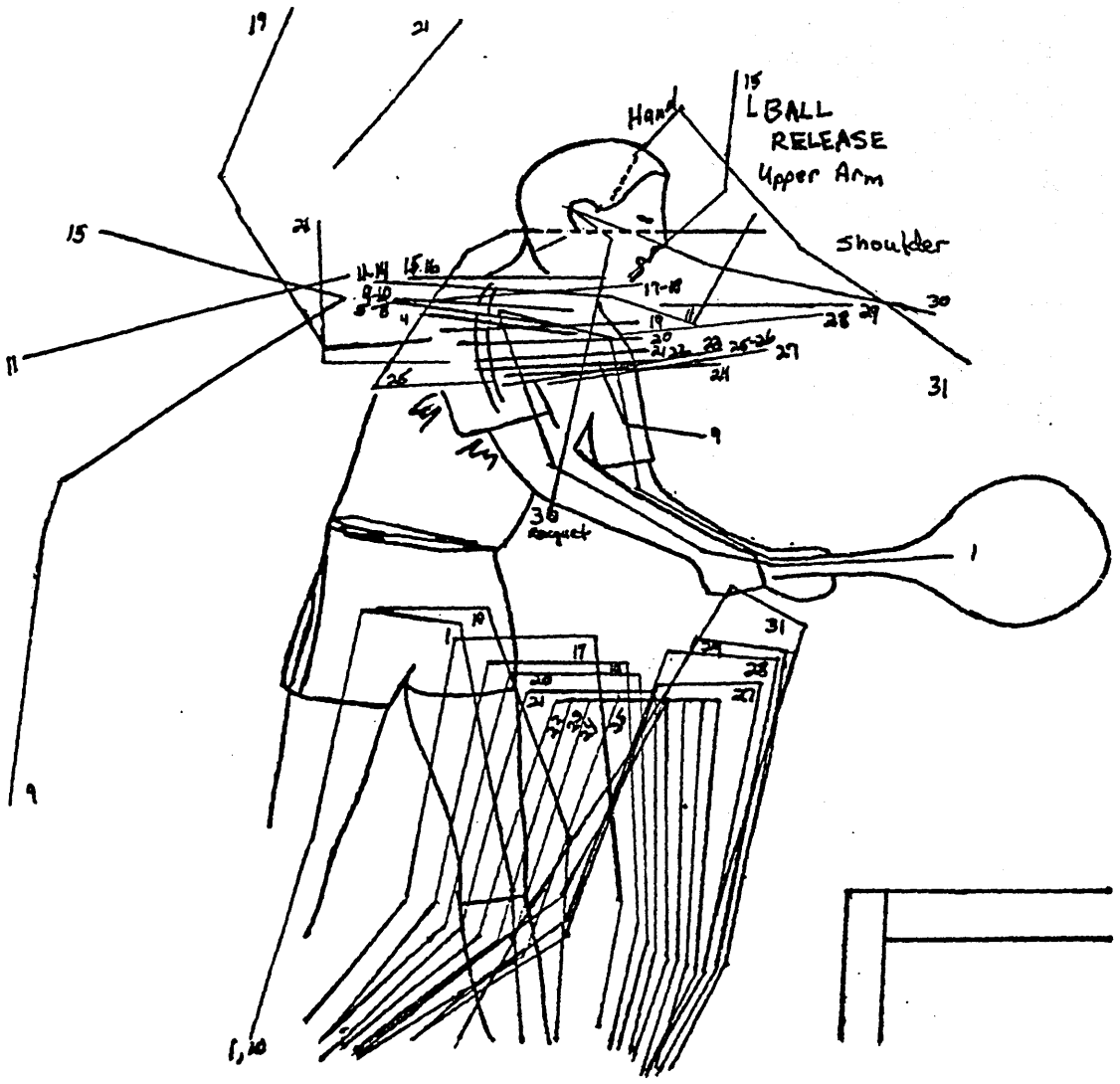

Figure 18. Side view of shoulders.

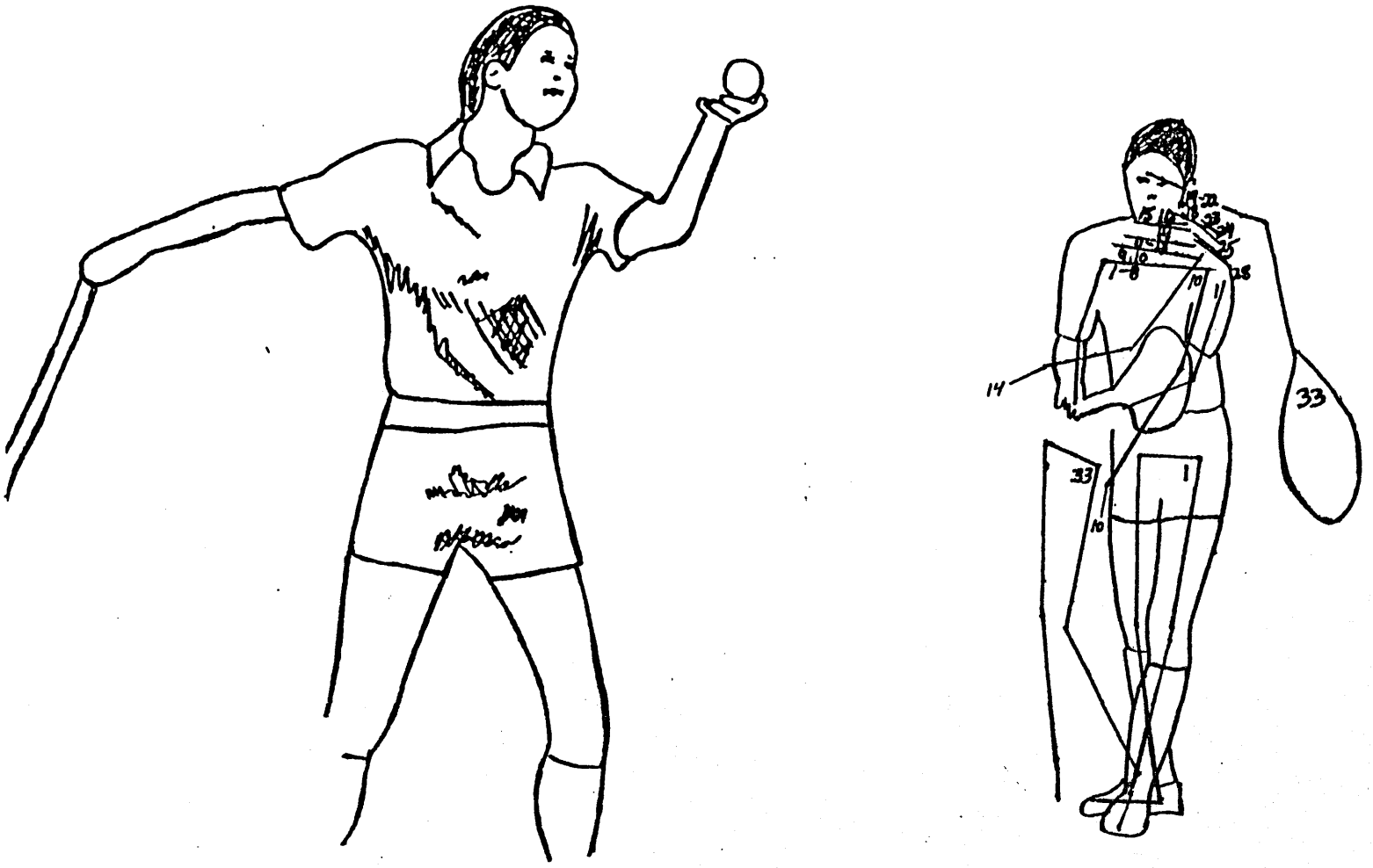

Figure 19. Ball release and front view of the shoulders.

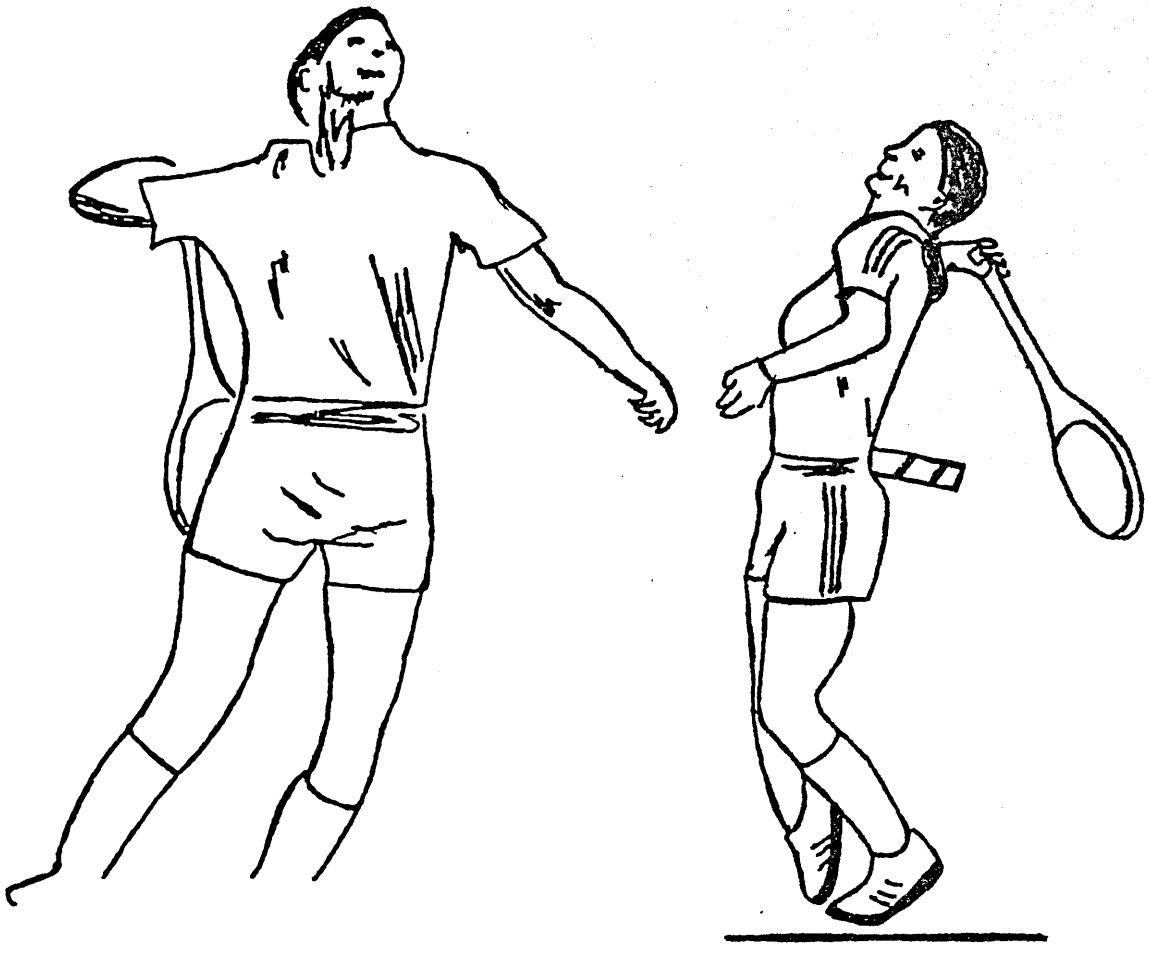

Figure 20. Frame 32 and Position 22 of Figure 37.

Figure 21. Frame 33 and Position 23 of Figure 37.

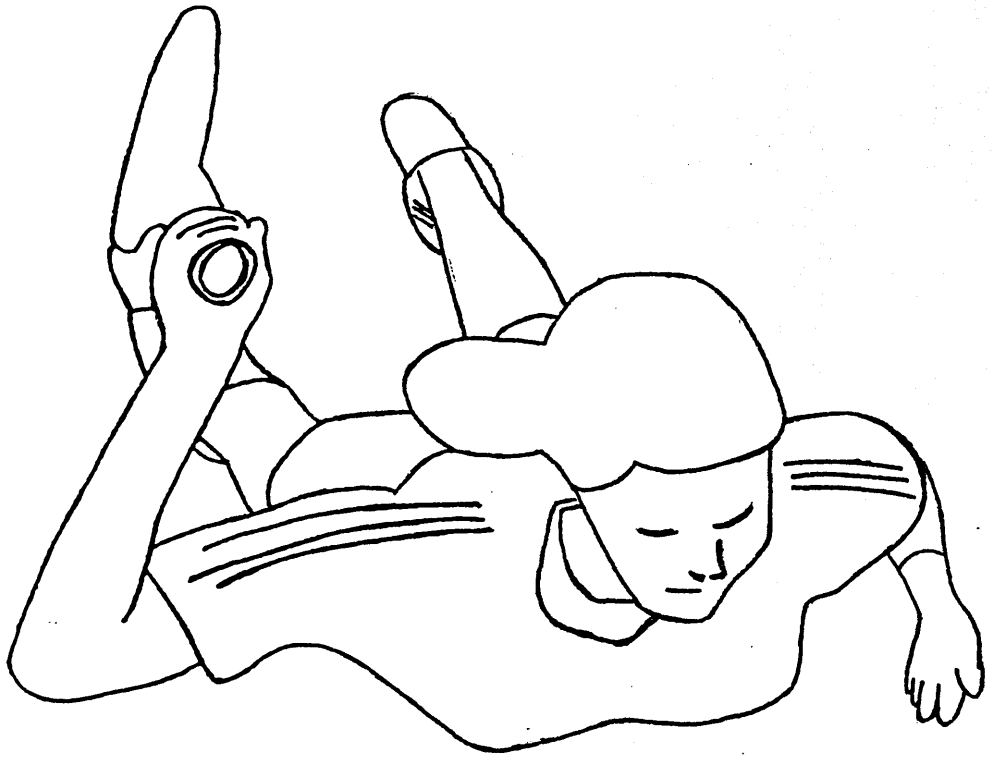

Figure 22. Backscratch position.

Table 2

Shoulder Degrees from Tracing and Lamb.4

Frame	Tracing (Degrees)	Time	Frame	Lamb.4 (Degrees)	Time
1	166	0.049	1	170	0.033
2		0.098	2	171	0.066
3		0.147	3	171	0.099
4	172	0.196	4	171	0.132
5	172	0.245	5	172	0.165
6	172	0.294	6	173	0.198
7	172	0.343	7	173	0.231
8	172	0.392	8	171	0.264
9	177	0.441	9	172	0.297
10	177	0.490	10	171	0.330
11	176.5	0.539	11	174	0.363
12	176.5	0.588	12	174	0.396
13	176.5	0.637	13	174	0.429
14	176.5	0.668	14	174	0.462
15	180	0.699	15	177	0.495
16	180	0.730	16	176	0.528
17	185	0.761	17	179	0.561
18	185	0.792	18	178	0.594
19	183	0.823	19	178	0.627
20	182	0.854	20	180	0.660
21	183	0.885	21	179	0.693
22	183	0.916	22	183	0.726
23	183	0.947	23	184	0.759
24	180	0.978	24	187	0.792
25	189	1.009	25	186	0.825
26	189	1.040	26	188	0.858
27	188	1.071	27	188	0.891
28	185	1.102	28	189	0.924
29	180	1.133	29	191	0.957
30	170	1.164	30	191	0.990
			31	188	1.023
			32	188	1.056
			33	188	1.089

abducted. The tossing arm continued to be adducted (see

figures 23 and 24).

In Frame 34, the subject was moving out of the "backscratch " position (see Figure 25). The right foot was almost off the court, and the right knee was extended. The right upper arm was inwardly rotated and abducted. The trunk was laterally flexed to the left and hyperextended with the left shoulder positioned in front of the front foot. Frame 35 was a continuation of Frame 34 (see Figure 26). The right foot was off the court, and the leg was hyperextended but moving toward the net. The left leg was extended. As the right shoulder was abducted, the left shoulder was adducted. The right forearm was extending and the wrist was hyperextended. The spine was laterally flexed to the left.

In Frame 36, the knees were extended and the left toe was barely touching the court (see Figure 27). The right forearm was extending, and the upper arm was abducting. The right hip was no longer hyperextended because the spine was flexed and laterally flexed to the left.

Frame 37 showed ball contact (see Figure 28). The ball was contacted to the right and slightly in front of the head with the elbow extended and the wrist hyperextended. The trunk was slightly flexed to the left,

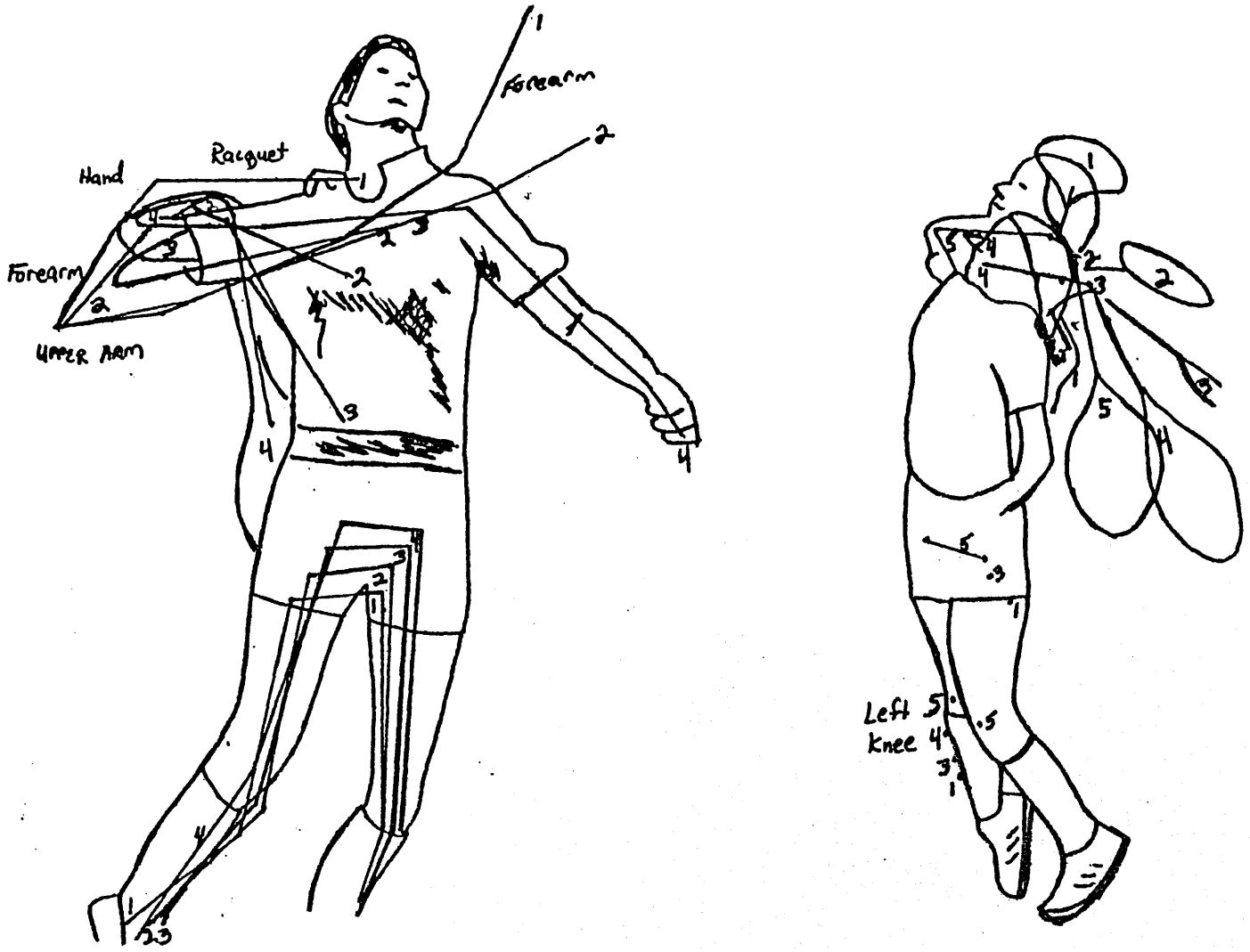

Figure 23. Motion coming out of the backscratch position and moving into it.

Figure 24. Coming out of the backscratch position.

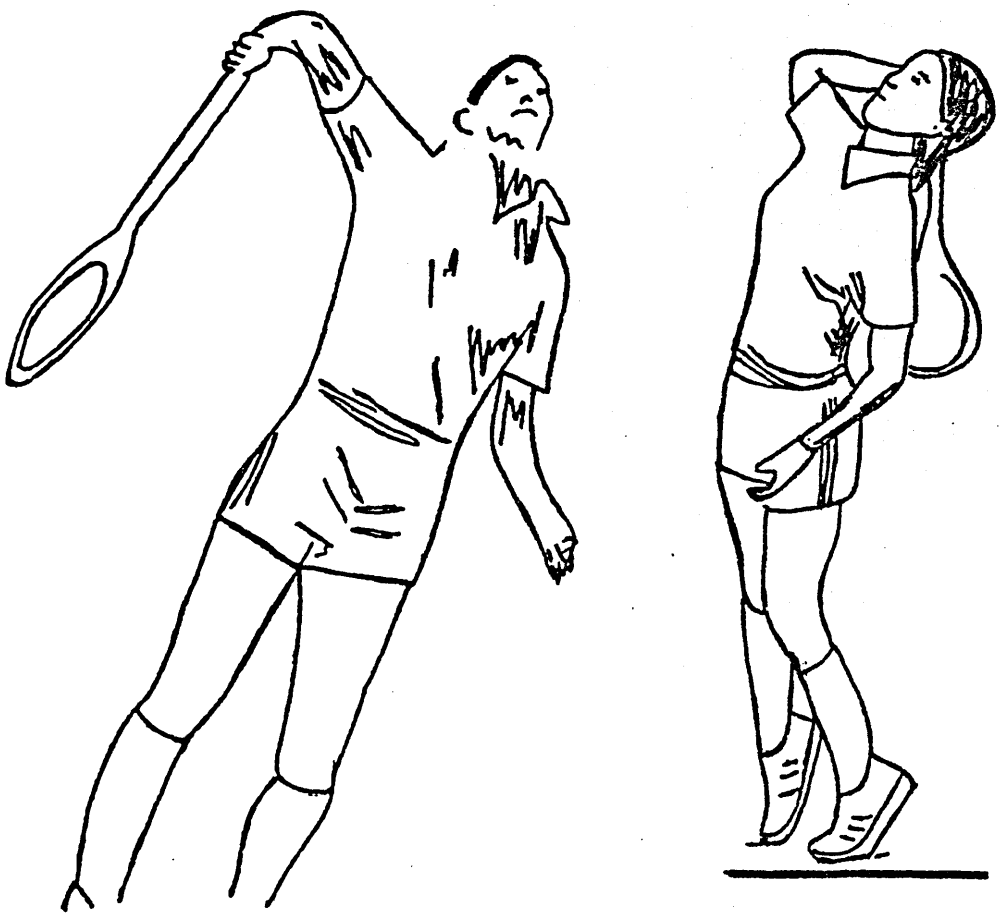

Figure 25. Frame 34 and Position 24 of Figure 37.

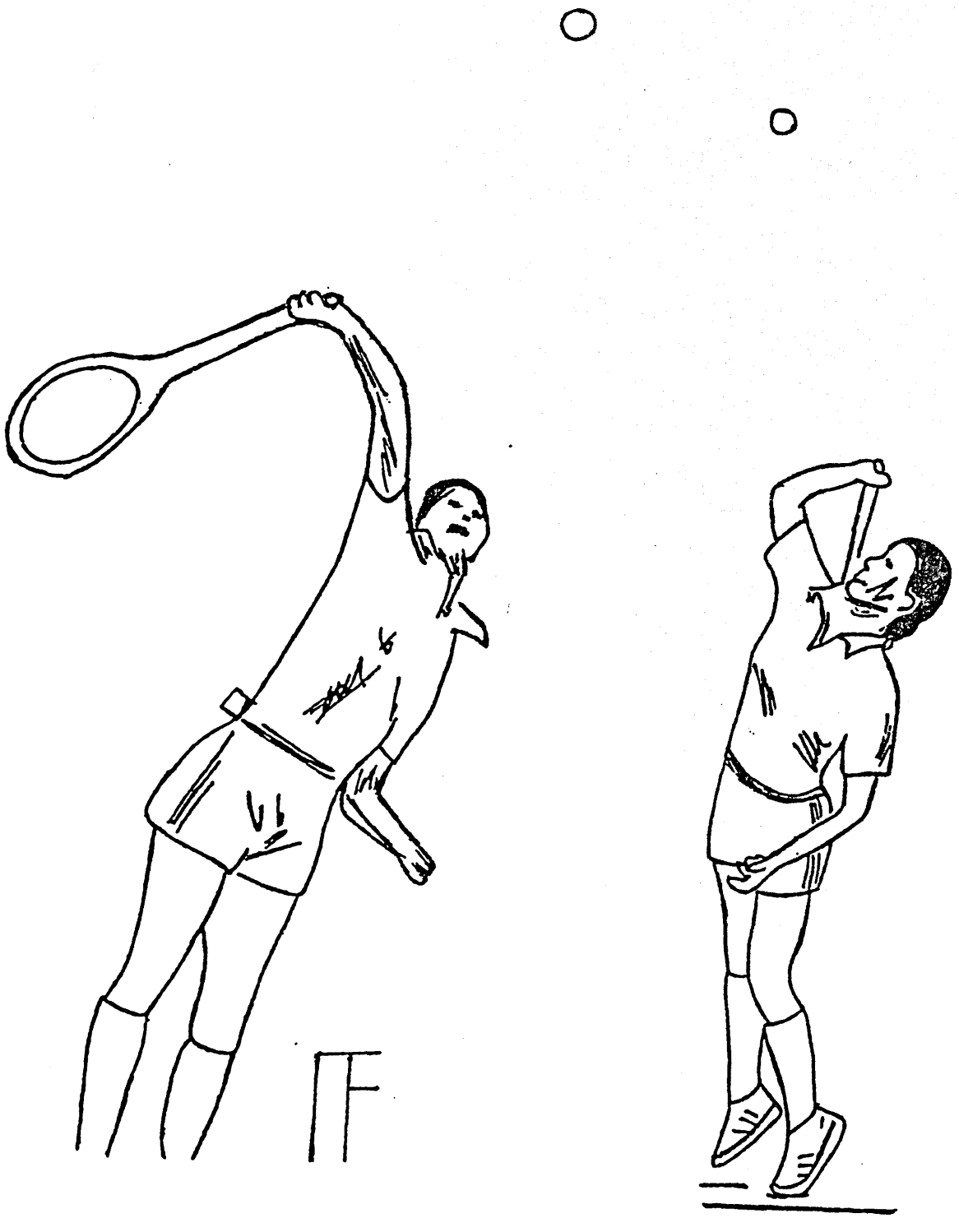

Figure 26. Frame 35 and Position 25 of Figure 37.

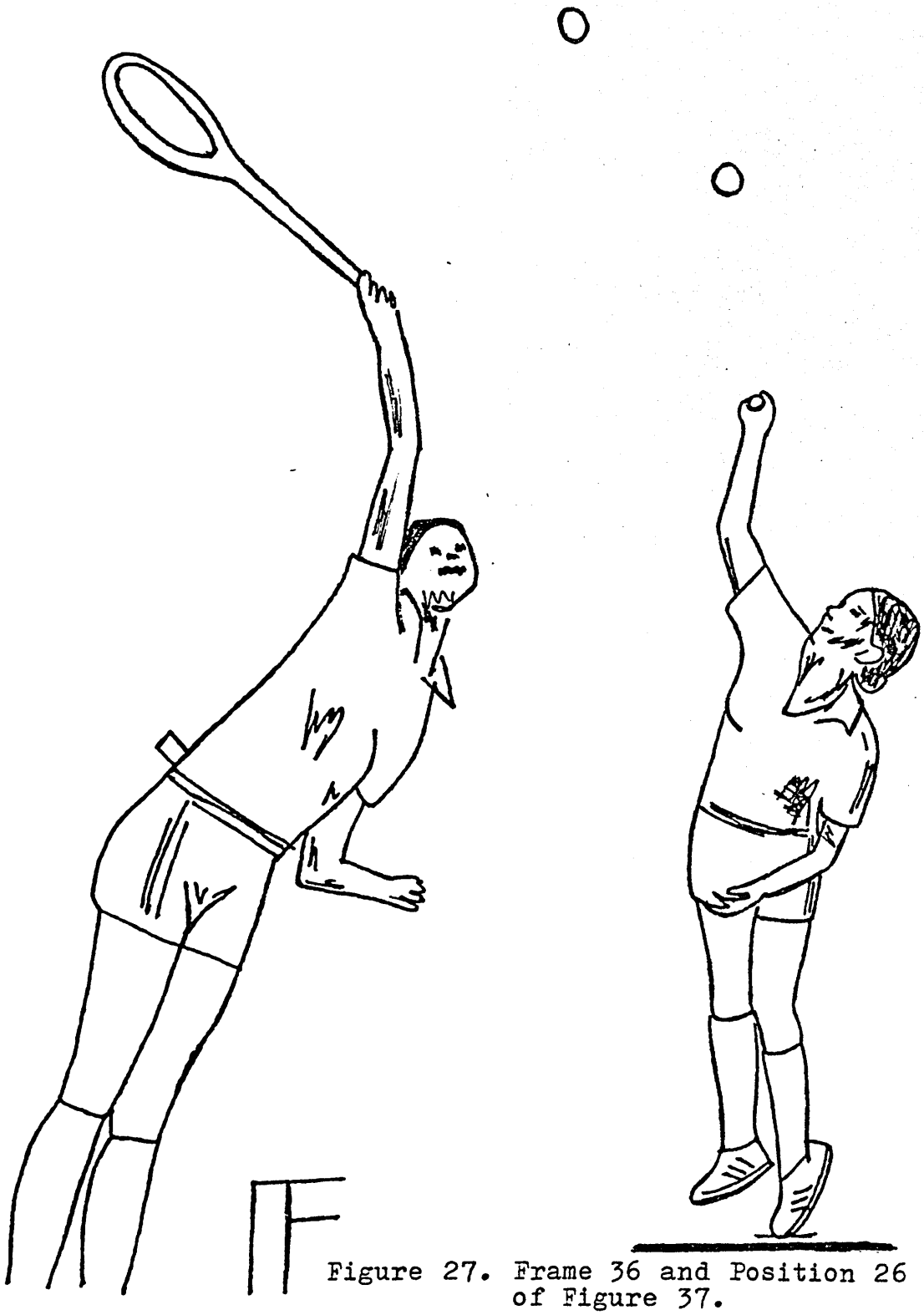

Figure 27. Frame 36 and Position 26 of Figure 37.

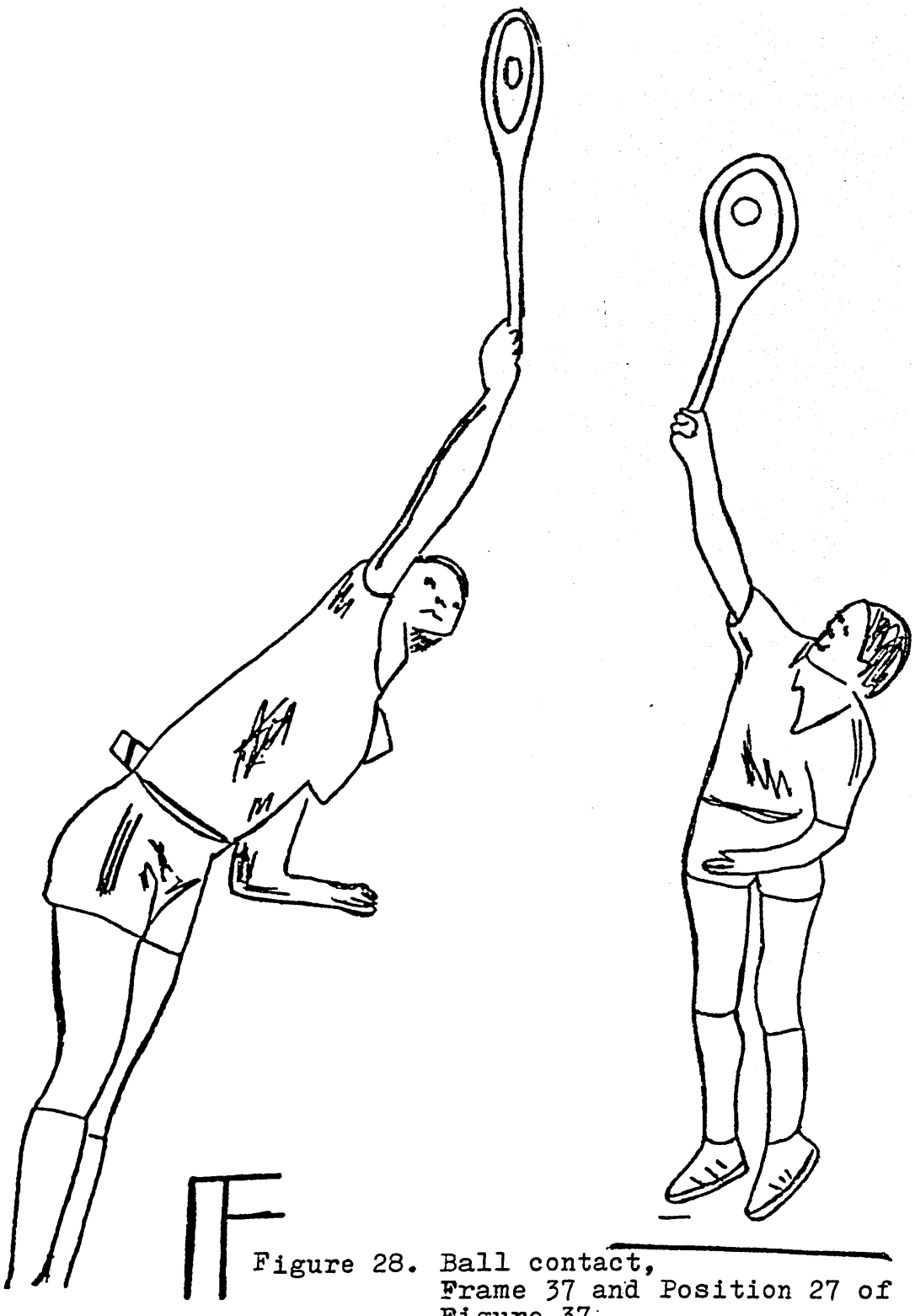

Figure 28. Ball contact, Frame 37 and Position 27 of Figure 37.

and the shoulders were almost parallel to the net (26 degrees to the baseline). The knees were extended before the elbow was extended; the elbow was extended three frames prior to contact. Both feet were off the court. In the side view, the spine was flexed at an angle of 51 degrees, the upper arm was at 60 degrees, and the wrist was at 94 degrees (see figures 29 and 30).

Figures 29, 30, and 31 show that hip and leg extension occurred prior to ball contact. Position 1 of Figure 29 shows that the hips were slightly rotated toward the back fence; in positions 2 and 3, the hips were perpendicular to the net, and in positions 4-6, the hips were rotating counterclockwise to face the net. The knee flexion can be seen in positions 1-3 (previous to the backscratch position) and the extension in positions 4-6. Knee extension can also be seen in Figure 30. In Position 1, the racquet face was over the head. Halfway between positions 4 and 5, the knees were fully extended. In Position 5, the right foot was off the court.

Frames 38, 39, and 41 show the follow-through. In Frame 38, the right leg was flexed past the left leg which was hyperextending (see Figure 32). The upper arm inwardly rotated to cause the racquet face to turn

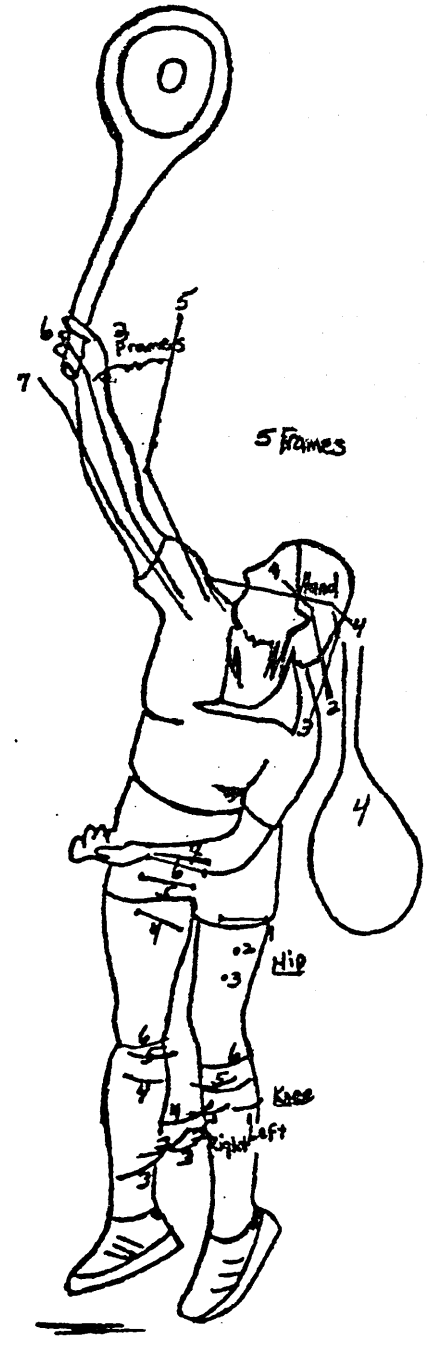

Figure 29

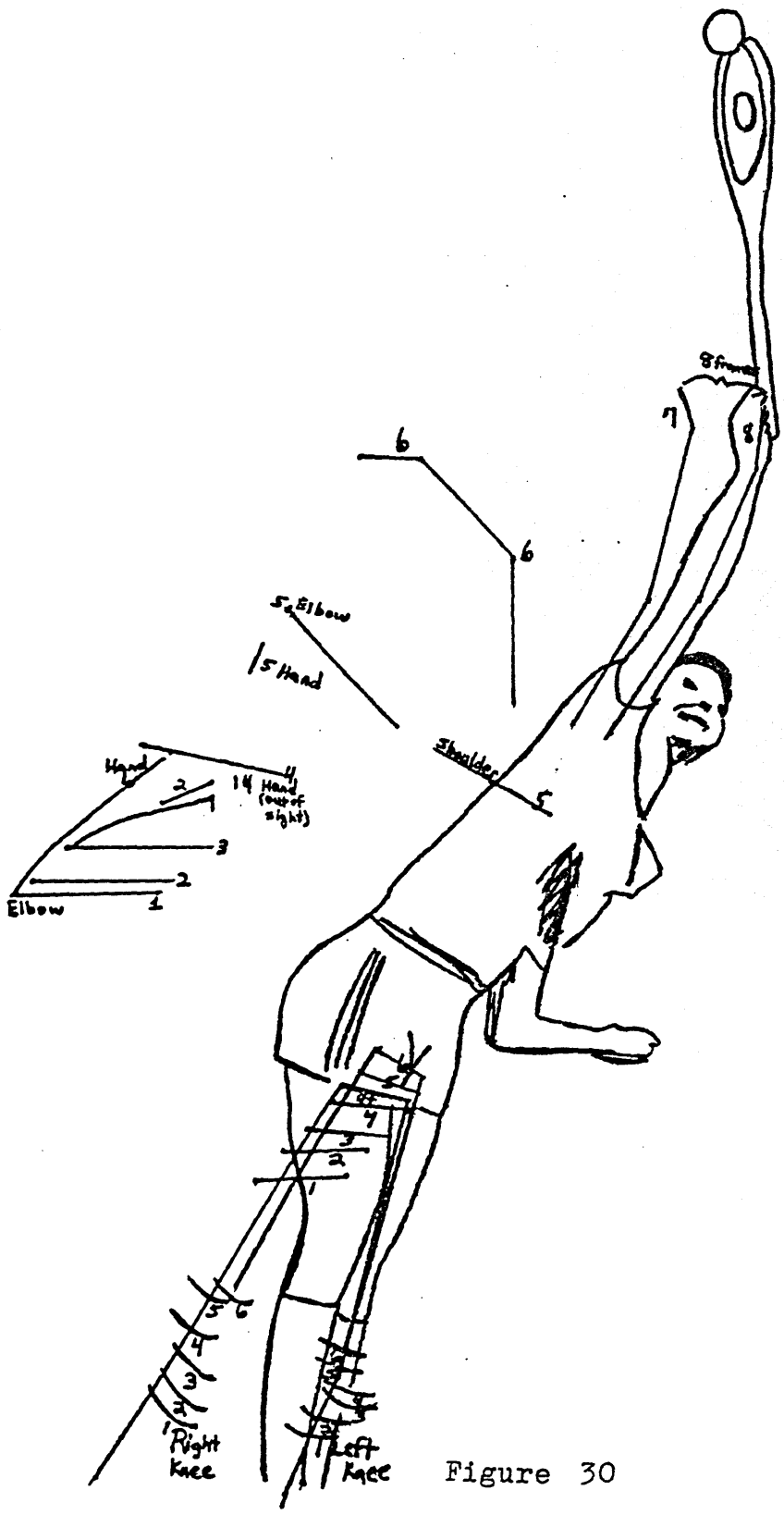
8 Forearm
7
8
6
6
5 Elbow
5 Hand
Shoulder
5
Hand
4
2
1
4 Hand (out of sight)
3
2
Elbow
1
7
6
5
4
3
2
1
Right knee
Left knee

Figure 30

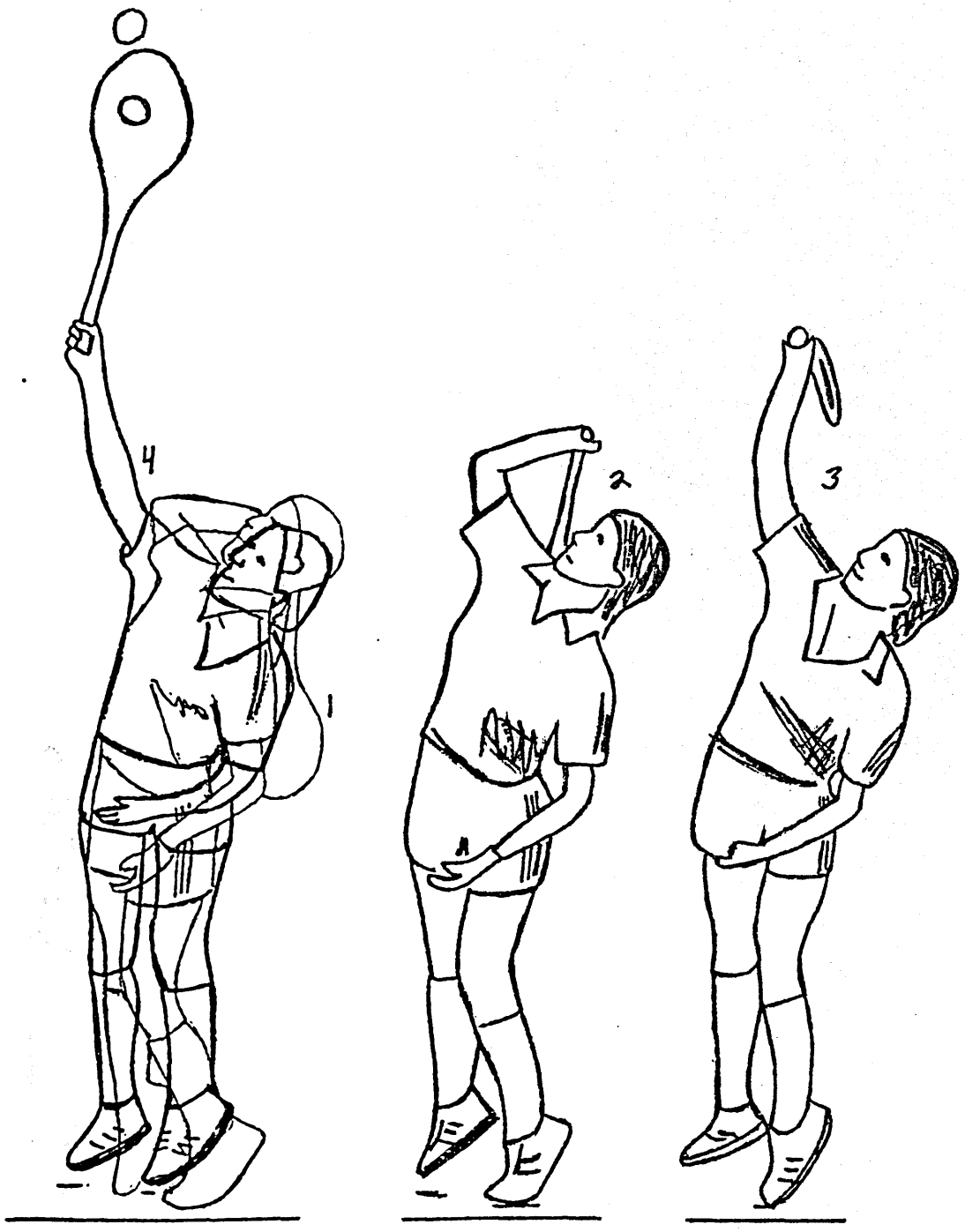

Figure 31

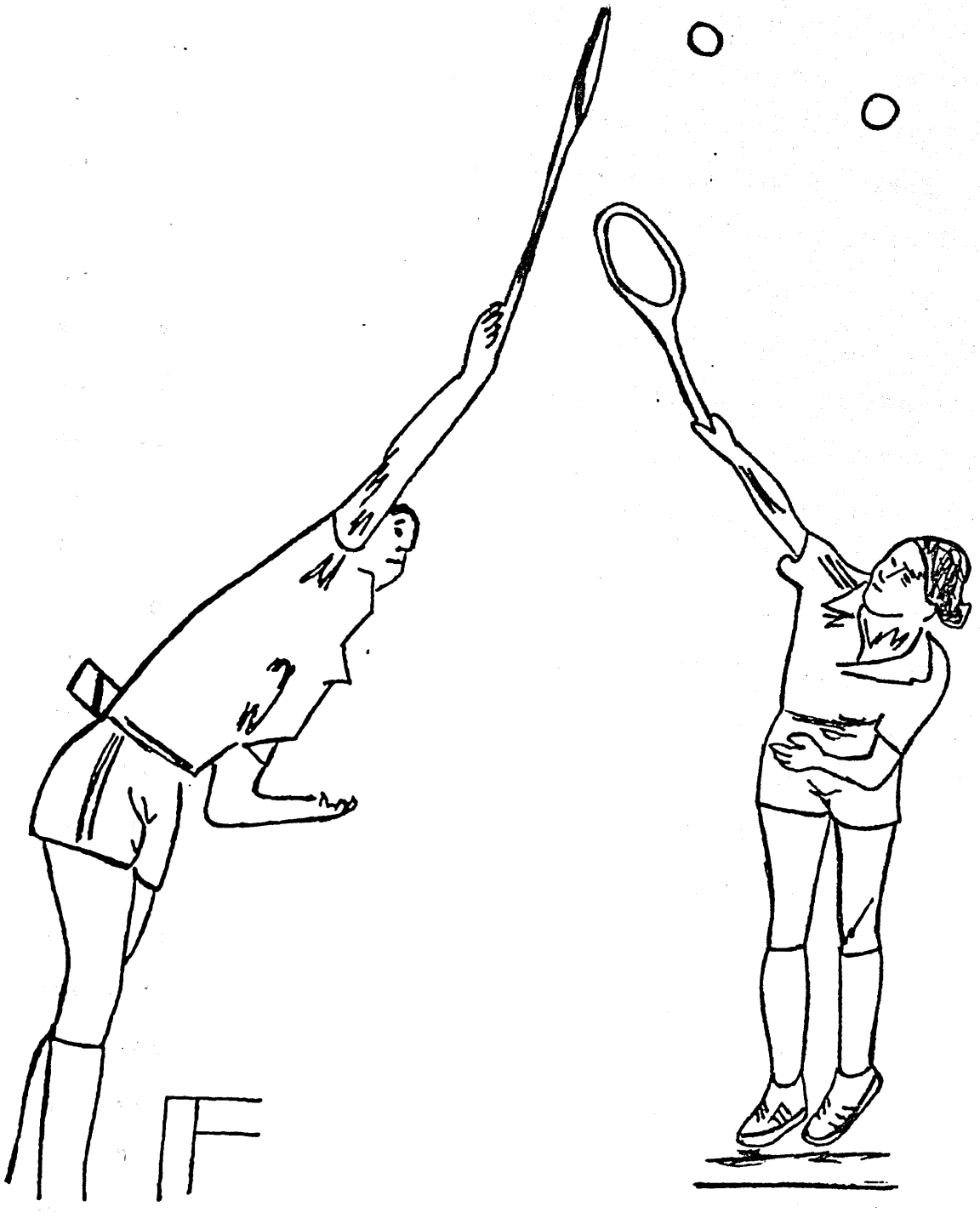

Figure 32. Frame 38 and Position 28 of Figure 37.

outward. This rotation appeared to reduce muscle tension by positioning the shoulder in a non-stressful position (Plagenhoef, 1970). The racquet arm was extended overhead. In Frame 39, the spine continued to flex and the right hip joint hyperextended and the left hip joint flexed. The palm was pronating and the racquet arm was still extended overhead (see Figure 33). In Frame 41, the right foot touched the court in front of the baseline. The upper arm had inwardly rotated and the elbow had flexed. The body was squarely facing the net (see Figure 34).

The hip and shoulder rotations were traced using serve 7 (see figures 35 and 36). The hips were traced every 15 frames and the shoulders every 10 frames.

The hips began at approximately 45 degrees to the baseline in Position 1. They were not rotated in positions 1-9 although they were moved linearly toward the back fence to Position 9. In Position 10, they were rotating clockwise with increasing velocity, and were moved forward toward the baseline. At ball release, the hips were approximately 90 degrees to the baseline.

The hips were rotated 19 degrees from Position 1 to Position 19 and 20 degrees from Positions 19 to 36. At

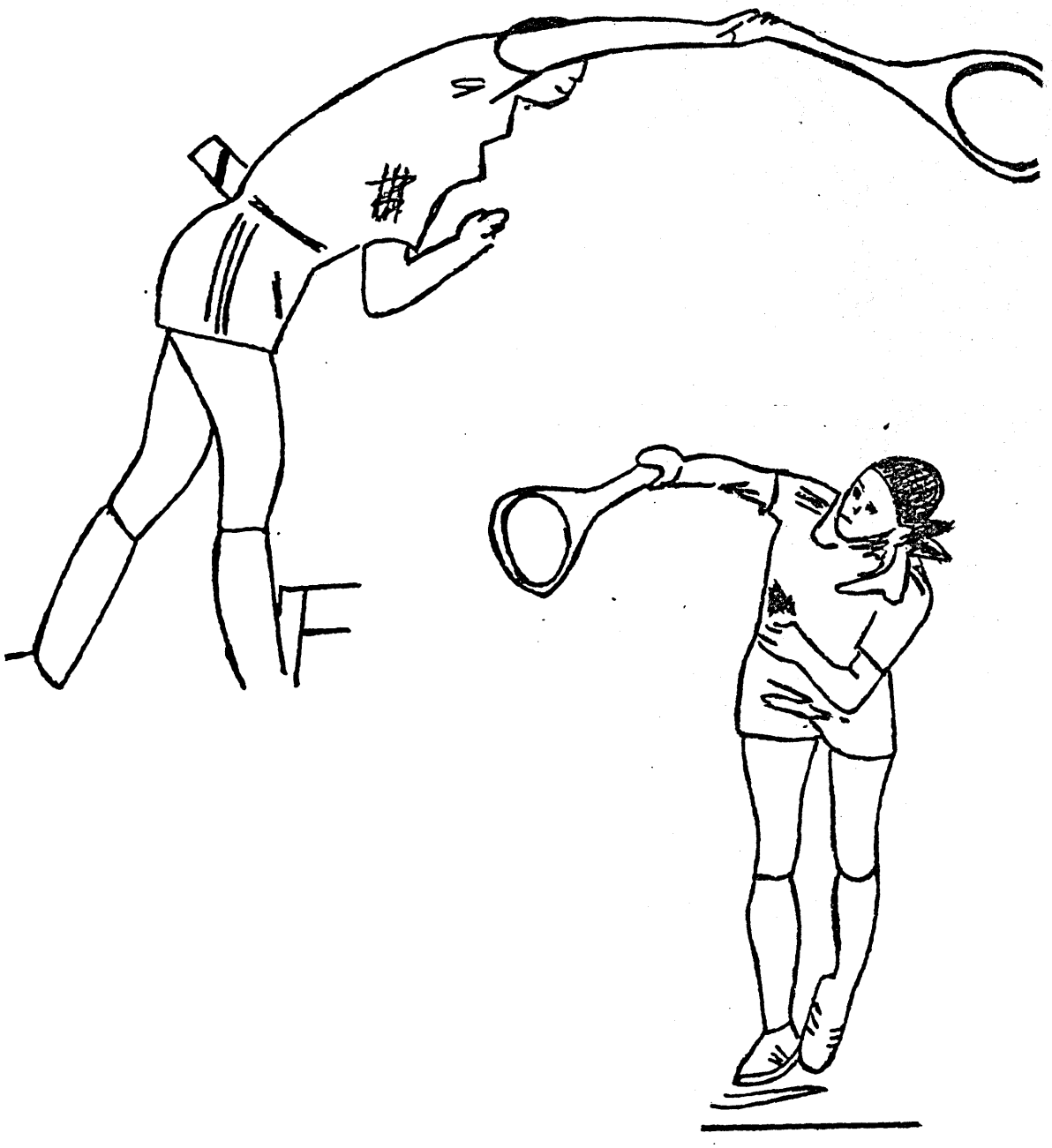

Figure 33. Frame 39 and Position 29 of Figure 37.

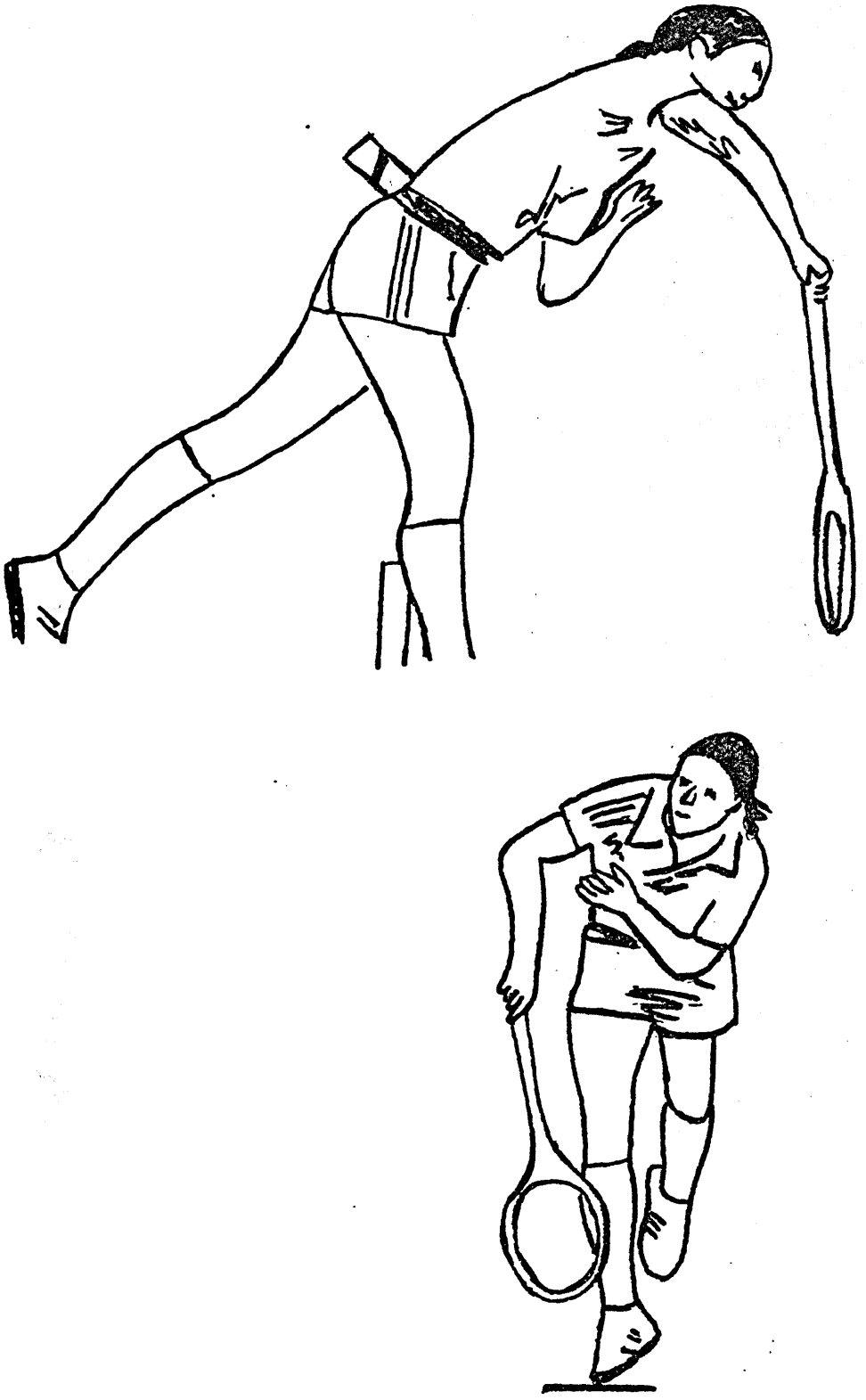

Figure 34. Frame 41 and Position 30 of Figure 37.

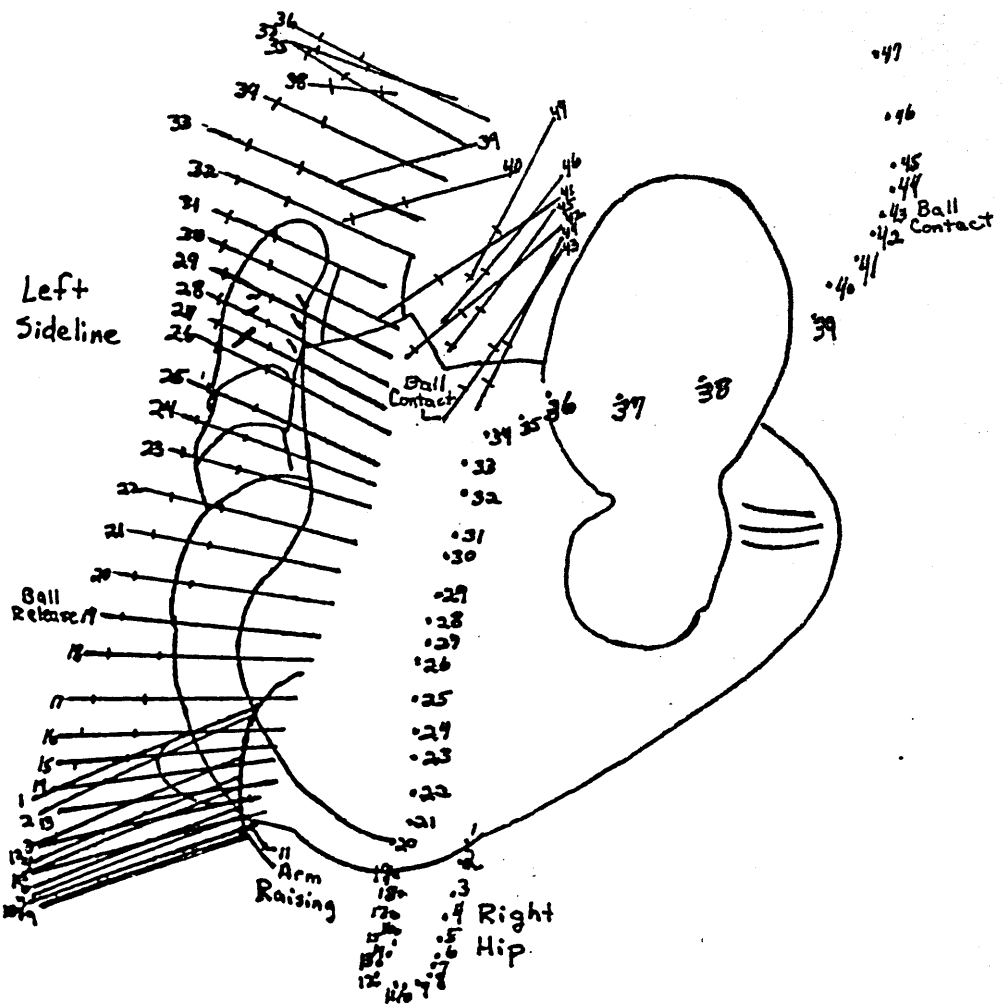

Figure 35. Hip rotation.

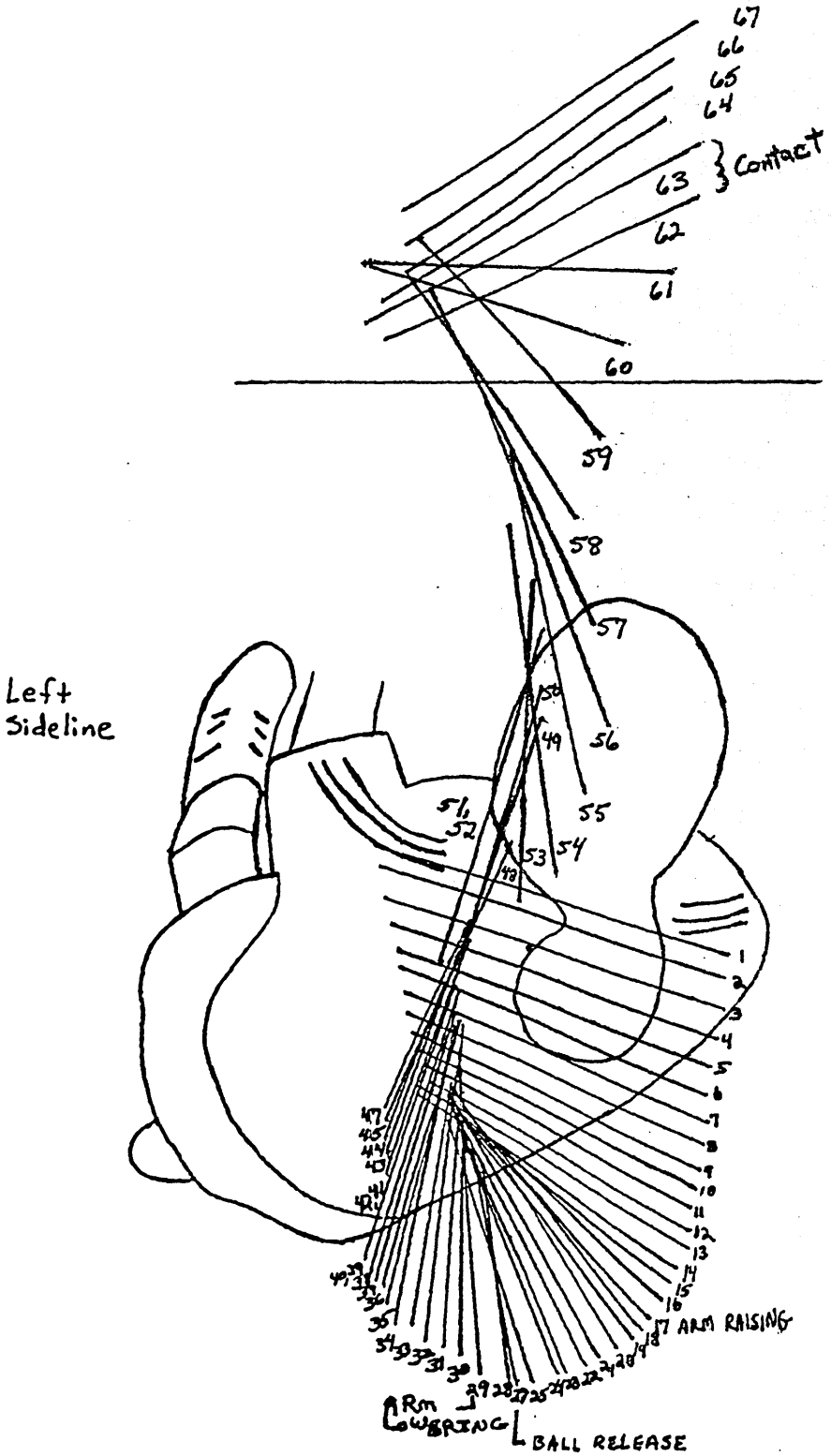

Figure 36. Shoulder rotation.

Position 36, the rotation was changed from clockwise to counterclockwise direction. Until Position 36, the left hip was closer to the net than the right hip. At Position 36, the velocity of the rotation of the hips was increased and the right hip was moved toward the baseline as the left hip moved toward the back fence. At ball contact, however, the left hip remained in front of the right hip. The hips rotated 86 degrees from positions 36 to 43. The angular displacement previous to contact was 39 degrees. After contact, the hips were rotated 8 degrees to Position 47.

The shoulders were positioned, initially, at less than 45 degrees to the baseline. From positions 1-14, the shoulders were moved clockwise toward the back fence. In Position 16, before the tossing arm started to flex , the left shoulder was held stationary and served as a pivot point as the right shoulder continued to move clockwise toward the left sideline. At ball release (Position 27), the shoulders were nearly perpendicular to the baseline (80 degrees). The amount of rotation from positions 1 to 27 was 62 degrees. After ball release, the shoulders were rotated clockwise toward the left sideline and moved forward toward the baseline. From positions 27-47, the

rotation was 31 degrees. From Position 47 to ball contact, the shoulders were moved forward and counterclockwise as their velocity was increased . At contact, the right shoulder was past the left. The angular displacement before contact was 93 degrees. The shoulders were rotated 10 degrees after ball contact (see Table 3).

The racquet and ball velocities were determined previous to and after contact of the ball. The racquet velocity at two frames before contact was 95.5 ft./sec. For three frames after contact, the racquet velocity was 89.07 ft./sec., decreasing to 59.39 ft./sec. in the fourth and fifth frames.

A ball velocity of 92.76 ft./sec. was determined for the first 2 frames after contact. The time was .0054 seconds. The velocity in frames 3 through 5 was 96.53 ft./sec. for a total of 0.0119 seconds. In frames 6 and 7, the velocity decreased to 88.89 ft./sec. at 0.0173 seconds. In Table 4 are presented the racquet and ball velocities.

The body movement was sequential during the serve. Based on a relative comparison, the knees were extending 4 frames before contact, the hips were rotated 3 frames

Table 3

Hip and Shoulder Rotation

Positions	Hip Rotation (Direction)	Degrees
1-9	toward the fence	0
9-19	clockwise and toward net to ball release	19
19-36	clockwise to change of direction	20
36-43	counterclockwise to ball contact	86
43-47	counterclockwise	8

Positions	Shoulder Rotation (Direction)	Degrees
1-27	clockwise toward fence to ball release	62
27-47	clockwise to change of direction	31
47-63	counterclockwise to ball contact	132
63-67	counterclockwise	10

Table 4

Racquet and Ball Velocity

Racquet		Ball	
Ft./sec.	(sec.)	Ft./sec.	(sec.)
104.90	0.0021		
95.50	0.0042		
95.50	0.0063		
Contact		Contact	
89.07	0.0027	92.76	0.0027
89.07	0.0054	92.76	0.0054
89.07	0.0071	96.53	0.0071
59.39	0.0092	96.53	0.0092
59.39	0.0119	96.53	0.0119
		88.98	0.0146
		88.98	0.0173

before contact, and the shoulders were rotated 1 frame before contact. The elbow was not extended until contact and the wrist was flexed after contact.

In the text that follows, reference is made to the figure which presents a tracing of the frame noted. The captions of those figures to which the reader is referred indicate, in turn, the corresponding positions of the subject in the composite tracing in Figure 37.

The motion of the entire serve with weight transfer can be seen in Figure 37. The subject began the serve with the weight on the front foot. The weight continued toward the back fence to Frame 5 (Figure 4). Figure 37

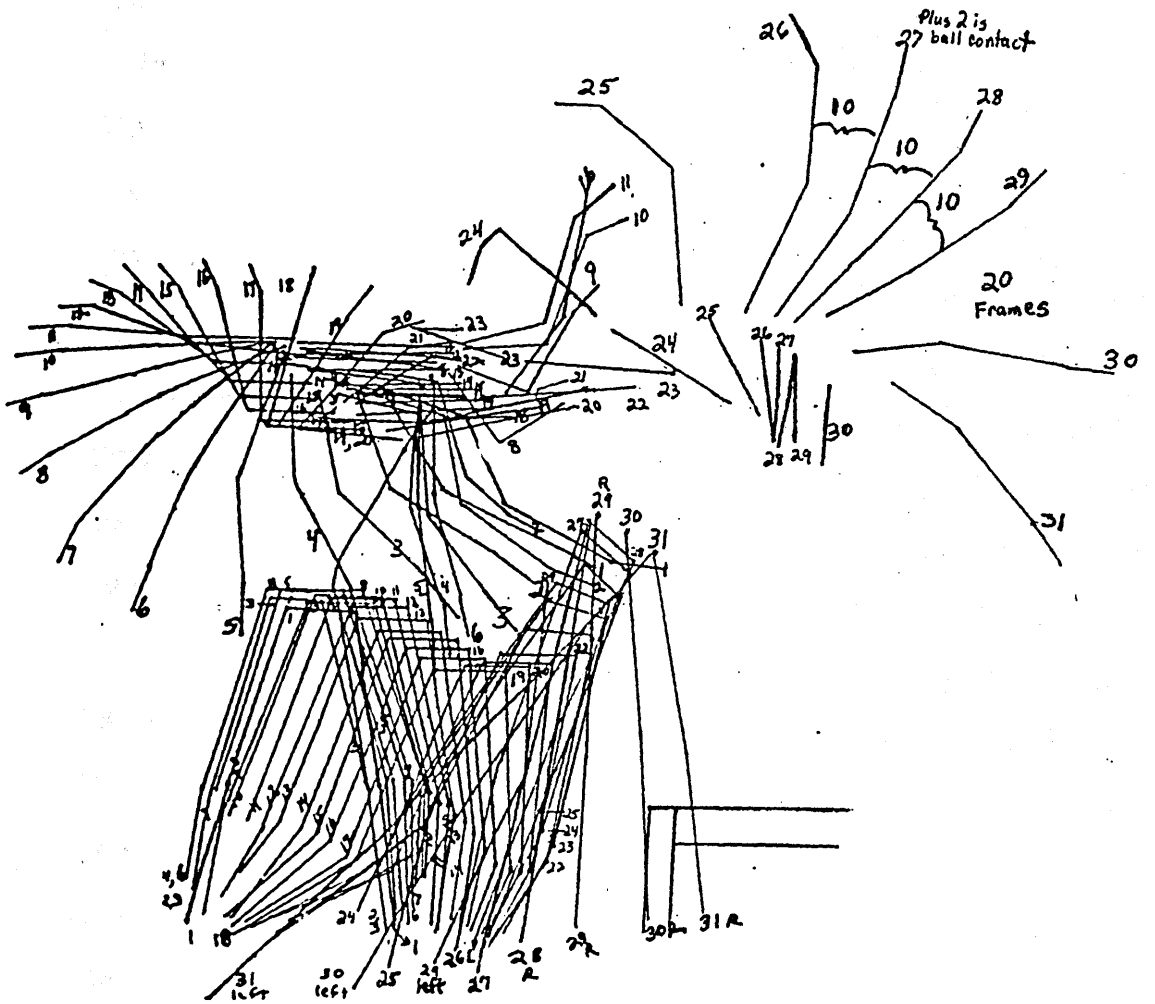

Figure 37. Entire service motion traced every 20 frames.

was traced every 20 frames.

From frames 5-11 (Figures 4, 5, & 10), the weight was positioned over both feet as the hips continued to move clockwise; the left knee was being flexed as the hips rotated. The racquet arm was moved from in front of the body to past the right hip. In Frame 8 (Figure 5), the tossing arm was near the thigh. Starting at Frame 11 (Figure 10), the knees were being flexed and caused the weight to move forward. The arms were at approximately a 45 degree angle to the trunk. Flexion of the knees (20 degrees) was continued to Frame 29 (Figure 17) and extension was begun at Frame 30 (Position 20 of Figure 37). In Frame 29 (Figure 17), the upper arm of the racquet arm was parallel to the court, and the forearm was flexed to 56 degrees. At Frame 35 (Figure 26), the knees were extended, the upper arm was at 96 degrees to the court, and the forearm was at 139 degrees to the court. The shoulders were over the baseline. Between frames 37 and 40 (figures 28, 32, & 33), the shoulders were perpendicular to the baseline. At ball contact in Frame 37 (Figure 27), the racquet arm was extended to a point in front of the shoulders. The upper arm remained at shoulder level on the follow-through; the elbow was flexed

before the upper arm lowered to the trunk.

Table 5 is a comparison of the numbered frame intervals digitized for Figure 37 to those intervals used for the Lamb.4 program . Figure 37 presents data that were digitized every 20 frames; the Lamb.4 was separated into the sequences of 10, 16, and 12 frames.

Interpretation of Velocity and Acceleration Graphs

The velocity curves of the body segments are presented in Figure 38 and the acceleration curves are shown in Figure 39. The left foot and ankle did not appear in the side view of the film, thus lowering the reliability of the acceleration and velocity of the foot and the shank. Figure 37 is referred to in the following interpretation.

Velocity is a vector having magnitude and direction and is the "rate of displacement per unit time" (Le Veau, 1977, p. 162). Acceleration is the "rate at which the velocity changes with respect to time" (Hay, 1973, p. 18). A large increase in the units of displacement of a velocity curve indicates that the body segment moved a fairly large distance. In the acceleration graph, a sharp increase or decrease in a curve means that the segment

Table 5

Comparison of Figure 37 to Lamb.4

Figure 37		Lamb.4	
Frame:	1	Frame:	0
	2		1
	3		3
	4		5
	5		7
	6		9
	7		11
	8		13
	9		15
	ball toss		ball toss
	10		16
	11		18
	12		19
	13		20
	14		21
	15		23
	16		24
	17		25
	18		26
	19		28
	20		29
	21		30
	22		31
	23		33
	24		34
	25		35
	26		36
	27		37
	28		38
	29		39
	30		40
	31		42
		ball contact	

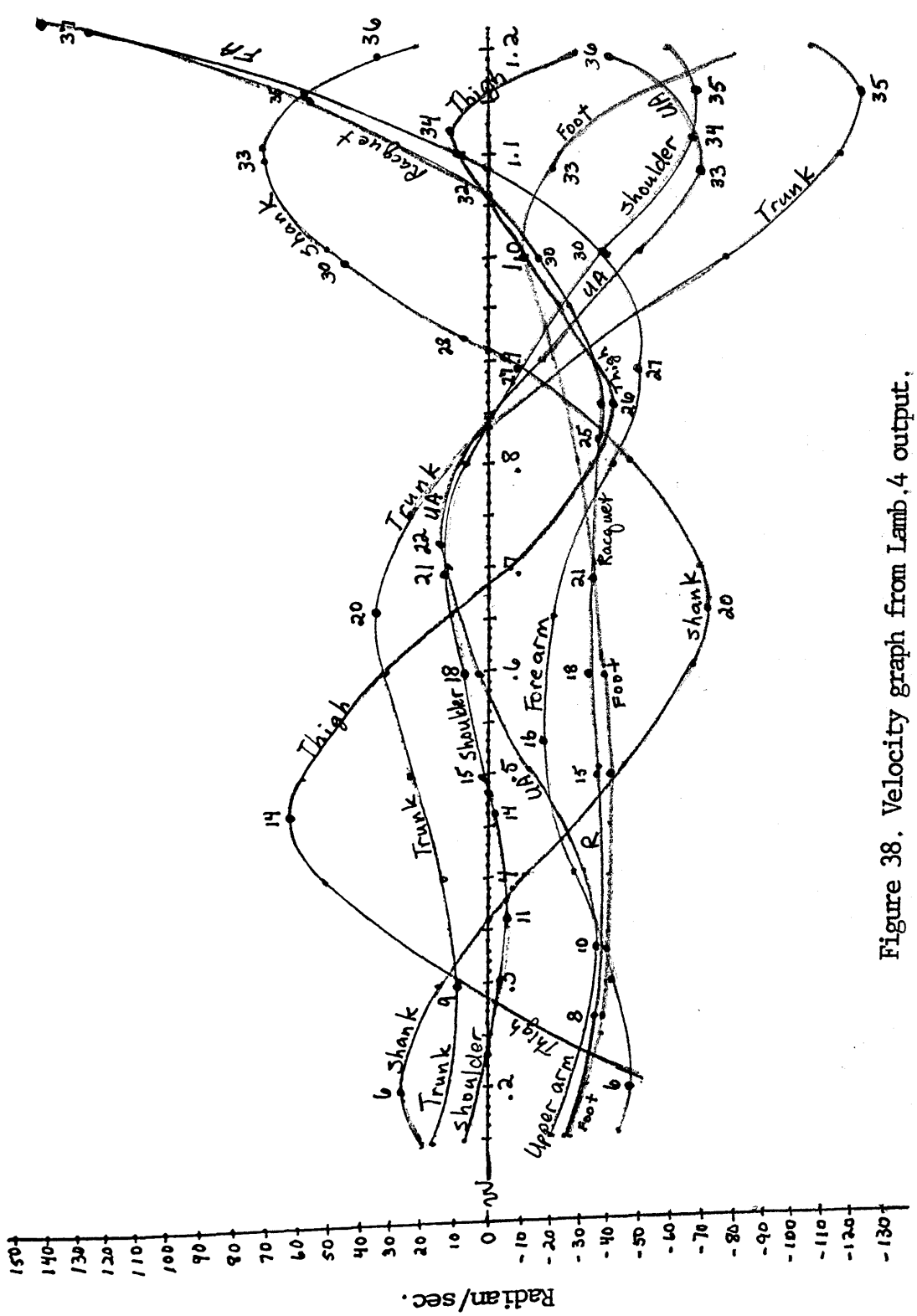

Figure 38. Velocity graph from Lamb.4 output.

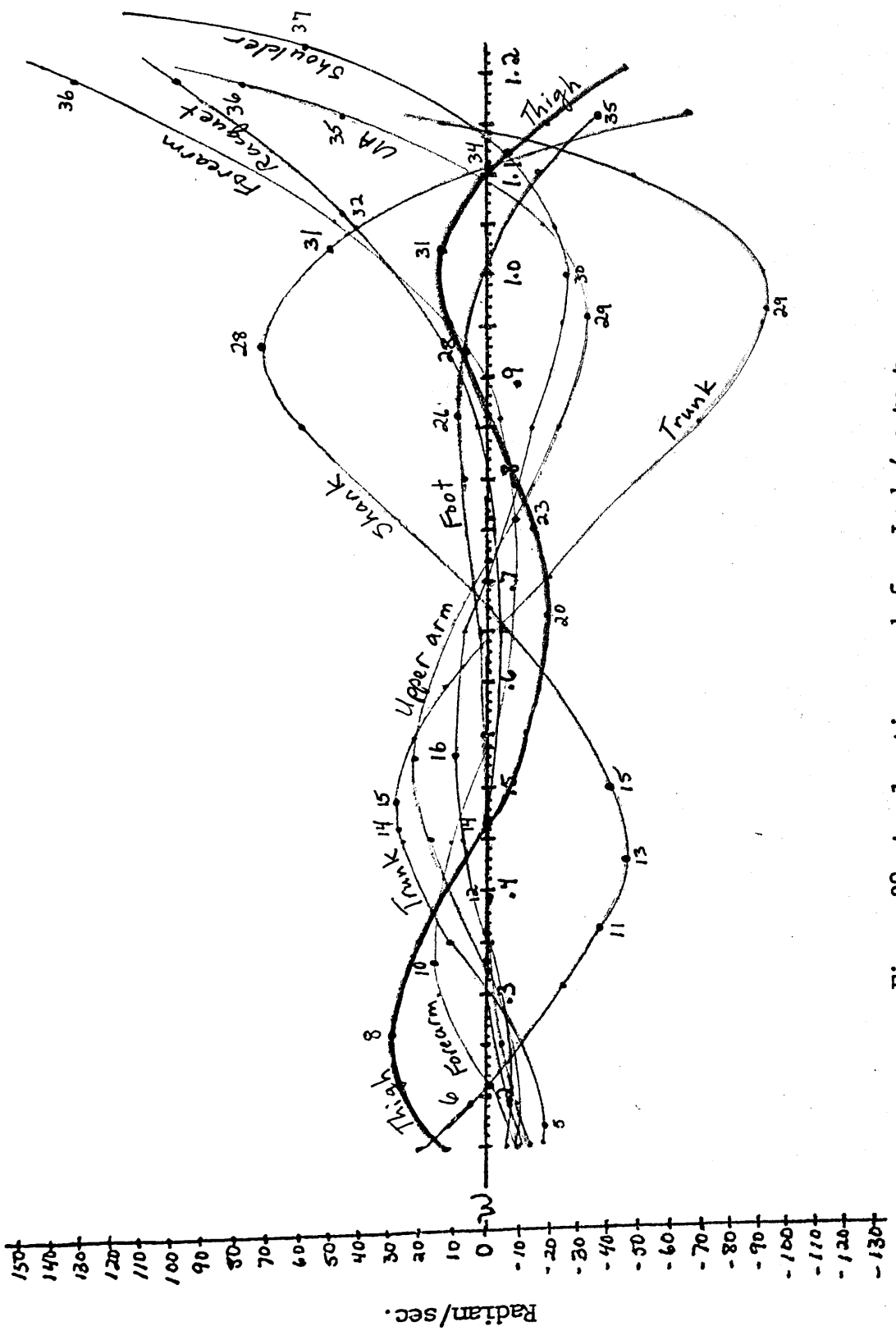

Figure 39. Acceleration graph from Lamb.4 output.

covered that distance either quickly or slowly. A sharp increase toward a peak in a velocity curve, relative to the rest of the curve, and an increase in the acceleration curve, shows that the segment had a positive velocity as it covered the distance and that the acceleration was also increasing.

The velocity graph shows that the left foot was moved toward the back fence during the entire serve. The velocity was positive through the first 9 frames, the frame in which the racquet arm was straight and just behind the right hip as it was raised from its perpendicular position to the court to a parallel position. In frames 10-30 (figures 10-17), slight distance was covered by the left foot and the velocity was negative. This indicates that the foot was slowing in preparation for a change of direction characterized by the curve crossing the baseline. In Frame 30 (Position 20 of Figure 37), the velocity became negative. The body had not reached the backscratch position so the foot remained stationary until Frame 35 (Figure 26). At this point the legs were extended, and the left foot did cover distance as it moved toward the back fence.

The most distance covered by the left foot while it

was in contact with the court was during frames 3-10 (figures 3, 4, 5, and 10) when the trunk was moved to a position perpendicular to the net. The foot was accelerated during this time. In Frame 26 (Figure 16), the acceleration became negative. The negative acceleration could possibly be counteracting the positive acceleration of the trunk.

The velocity of the left shank was positive during frames 3-6 (figures 3-5) as it moved toward the court (see Figure 37). The velocity was negative from frames 6-12 (figures 4, 5, 10, and 11) as the shank slowed to zero before it changed direction.

In Frame 12 (Figure 11), the shank continued moving toward the net, and the knees began flexing causing the shank to move toward the court. The velocity was positive to Frame 20 (Figure 14) at which point the velocity of the shank became negative to prepare for a direction change in Frame 28 (Figure 17). The shank did not actually change direction until Frame 30 (Position 20 of Figure 37), when the knee extended and the shank began moving toward the back fence. A possible cause for the early direction change may be that the knee continued on an even plane for two and a half frames before extension. The positive

velocity would indicate the distance traveled was toward the net as the shank increased velocity for extension. In Frame 33 (Figure 21), the velocity became negative as the knee slowed to reach its full extension in Frame 35 (Figure 26).

The acceleration curve shows that the shank had decelerated to Frame 13 (Figure 11). It accelerated to Frame 28 (Figure 16), as the knees flexed. Beginning with Frame 28, the shank decelerated as the forearm, upper arm, shoulders, trunk, and racquet accelerated to ball contact.

The velocity of the thigh in frames 4-10 (figures 4, 5, and 10), was negative as the thigh moved toward the net. In frames 10 to 14 (figures 10-12), the velocty increased as the thigh lowered at an angle of more than 90 degrees toward the court because the knees flexed. The beginning momentum of the trunk moving with the thigh toward the net and the court could account for the positive velocity.

In frames 14 to 22 (figures 11-14), the velocity was negative as the knee continued to flex. The velocity of the thigh possibly was negative to control the downward and forward momentum of the trunk's center of gravity. There was no change of direction at Frame 22 (figures

14-16). The velocity was positive in frames 22-26 (figures 14-16).

The velocity of the thigh was negative in frames 26-32 (figures 16, 17, and 20). This could have caused the shank to increase its velocity at Frame 28 (Figure 16). The thigh had a negative velocity as it moved from 94 degrees to 82 degrees. In frames 32-34 (figures 20, 21, and 25), the velocity was positive as the knee extended. The change of direction may be caused by the inclination of the thigh from more than 90 degrees to the court to less than 90 degrees to the court.

In frames 34-36 (figures 25-27), the velocity of the thigh was negative as the leg reached full extension. The direction of the thigh changed to move toward the back fence in Frame 36 (Figure 27) as the velocity increased.

The trunk continued to move toward the back fence until Frame 15 (Figure 12). The velocity was negative until Frame 9 (Figure 10) as the trunk slowed from extension, and positive to Frame 20 (Figure 14) when the knees were flexed and the trunk moved downward in the sagittal plane and toward the net. No change of direction indicated by the velocity was noted when the trunk moved downward. The velocity was negative in frames 20-25

(figures 14 and 15) when the trunk began to move more toward the net.

The trunk moved upward toward ball contact at Frame 32 (Figure 20). The velocity remained positive to Frame 35 (Figure 26) when the left leg was extended. The velocity was negative as the body slowed at the height of the jump. The trunk increased velocity 110 units in the 10 frames from 25-35, when it had the most influence on the serve.

The acceleration graph showed deceleration of 100 units from frames 20-29 (figures 14-17). There was acceleration of 130 units from frames 29-36 (figures 17, 20, 21, and 25-27).

The shoulders followed the movements of the trunk but changed direction more frequently. From frames 3-7 (figures 3-5), the velocity was negative as the shoulders were moved toward the fence and upward because the trunk straightened. From frames 7-11 (figures 5 and 10), the velocity was positive as the shoulders and trunk continued to raise. The change of direction at Frame 7 (Figure 5) may be related to the near horizontal position of the shoulders .

In frames 11-15 (figures 10-12), the shoulders slowed

to approach a change of direction. After the ball was released in Frame 15 (Figure 12), the shoulders began moving toward the net (as seen in Figure 36) with positive velocity.

From frames 21-24 (figures 14 and 15), the velocity decreased before another change of direction. This may have been related to the upward tilting of the shoulders. The shoulders continued moving toward the net and downward. In frames 24-34 (figures 15-17, 20, 21, and 25), the velocity increased as the shoulders moved toward the net. They moved 65 rad./sec. in these 10 frames. The shoulders were slowed in their velocity one frame before the upper arm began to slow velocity.

From frames 33-37 (figures 21 and 25-28), the acceleration curve increased 135 rad./sec. and the shoulders moved 90 degrees during the 4.5 frames. The velocity decreased because the upcoming change of direction before ball contact.

The velocity of the right upper arm was similar to the velocities of the trunk and shoulder. From frames 3-10 (figures 4, 5, and 10), the upper arm was moving with positive velocity toward the fence. In Frame 7 (Figure 5), the arm began to raise. In frames 10-17 (figures

10-13), the arm continued raising but the velocity decreased for the direction change. In Frame 18 (Figure 13), the arm began moving toward the net and downward as the knees flexed.

In frames 17-22 (figures 10-13), the velocity increased as the upper arm lowered toward the court. In frames 22-24 (figures 14 and 15), the upper arm decreased velocity as it neared a direction change. The change did not occur until Frame 30 (Position 20 of Figure 37), when the arm began moving upward to the backscratch position of Frame 33 (Figure 21). The velocity decreased to Frame 36 (Figure 27) as the arm was nearing a direction change before it would move toward the court.

The acceleration graph shows that the upper arm accelerated 114 rad./sec. from frames 29-36 (figures 17, 20, 21, and 25-27). From frames 16-29 (figures 13-17), the arm was decelerating.

The velocity curve of the right forearm basically followed the curves of the trunk, shoulder, and upper arm, except that the peak velocities appeared sooner. In frames 3-6 (figures 3 and 4), the velocity increased as the forearm moved toward the fence. The velocity decreased from frames 6-16 (figures 12-16), as the forearm moved

toward the back fence and upward. From frames 16-27 (figures 12-16), the velocity increased as the elbow flexed and the forearm began moving toward the net to Frame 19 (Figure 13), when a direction change was being approached.

The velocity of the right forearm decreased in frames 27-31 (figures 16, 17, and 20) as the arm was lowered to the backscratch position. The velocity then increased rapidly 125 rad./sec. from frames 31-37 (figures 20, 21, and 25-28) as the arm moved upward to ball contact. In frames 27-37 (figures 16, 17, 20, 21, and 25-28), the acceleration curve increased 160 rad./sec..

The velocity and acceleration curves of the racquet remained fairly constant to Frame 23 (Figure 14). There was a slight increase in velocity to Frame 8 (Figure 5) as the racquet lowered and moved toward the fence. The velocity remained positive to Frame 19 (Figure 13) as the racquet was moved toward the back fence and began moving over the head. It continued to move overhead to Frame 23 (Figure 14), but remained in front of the forehead. The velocity decreased in frames 23-32 (figures 14-17 and 20) as the racquet was moved into the backscratch position.

In frames 32-37 (figures 20, 21, and 25-28) the

velocity increased 135 rad./sec. and surpassed the forearm at Frame 36. The acceleration curve increased 105 rad./sec. from frames 25-37 (figures 15-17, 20, 21, and 25-28), 2 frames before the forearm accelerated.

A summary, a discussion of the results, conclusion, and recommendations for further study are presented in Chapter V.

CHAPTER V

SUMMARY, CONCLUSION, DISCUSSION, AND RECOMMENDATIONS FOR FURTHER STUDIES

In Chapter V, a summary of the thesis is given. A conclusion and discussion of the results are presented. Recommendations for further studies are suggested based upon the information the investigator has gained from this research.

Summary of the Investigation

The purpose of this study was to determine, through cinematography, whether a slice/topspin tennis serve was executed by a female professional according to the literature. The subject was filmed with high-speed cameras from three views; overhead, front, and side views. Sixteen mm , black and white, tri-x film was used.

The cameras were at right angles to each other. The front camera was across the net and protected by a plywood board. The overhead camera was placed on top of a scaffold directly above the subject. A telephone repair truck held the overhead cameraman. The origin for the three cameras was represented by a marker placed outside

of the center mark and the baseline. A reference box, visible to all cameras, was constructed to hold the trial sheets.

The filming occurred on May 2, 1980, at the tennis courts at Texas Woman's University in Denton, Texas. Three assistants operated the three cameras, a fourth collected tennis balls, and a fifth assistant recorded the service location and whether the serve was good or a fault.

The subject was given unlimited warm-up; when she was ready, instructions were given as to where to serve the ball. Those serves that best met the criterion of court placement were chosen for analysis.

The first serve was digitized from the front and side views. The side camera did not reach the appropriate film speed because insufficient time was allowed for the camera to attain maximum speed before the action occurred. The serve recorded by the camera having the highest speed was used for analysis. The speed of the front view camera was found to be accurate and was used as a standard for determination of the frame number to be digitized for the side view.

The two data files were submitted to three computer

programs. The files from the front and side view were combined to create three link systems which were treated by the Lamb program. These programs were combined to produce the final output, Lamb.4, which produced data for velocity, acceleration, segment angles, and smoothed displacement values. The data were analyzed and presented in appropriate tables and figures.

Results of the Study

The following results were those obtained from the study.

1. When tossing the ball, the palm was slightly supinated, not horizontal, and the elbow was not extended. The left foot had moved from nearly perpendicular to the net to a 45 degree angle.

2. The shoulders were rotated prior to the ball toss allowing the arm to ascend vertically to the baseline.

3. The weight began on the front foot, moved backwards over both feet as the tossing arm reached the thigh, and was forward when the arms were at a 45 degree angle.

4. The hands moved downward and upward at the same rate. To allow for this, the tossing arm

remained stationary one frame before flexing while the racquet arm crossed the trunk.

5. The kneebend, backbend, and the shoulder rotation began before the backscratch position.

6. The velocity of the upper arm decreased before contact, but the velocities of the forearm and the racquet increased. The hand and racquet were used as one segment for analysis.

7. The sequence of maximum deceleration before the serve was the shoulders, upper arm, trunk, shank, forearm, racquet, and thigh.

8. The shoulders remained horizontal from Frame 1 to between frames 30 and 33.

9. The shoulders rotated clockwise 62 degrees to the ball toss and continued 31 degrees to the counterclockwise change of direction. They rotated counterclockwise 132 degrees to ball contact and 10 degrees afterwards.

10. The hips did not sustain any movement toward the back fence. They rotated clockwise and toward the net 19 degrees to ball release. The hips continued moving clockwise for 20 degrees and then rotated 86 degrees counterclockwise to ball contact.

11. The tossing arm rotated clockwise with the shoulders before ball release; the arm was 7 degrees to the side of the shoulders and extended upward in line with the left thigh.

12. In the backscratch position, the palm of the racquet hand and the racquet face were parallel to the net. The wrist was slightly hyperextended. The upper arm and forearm were both parallel to the court, with the elbow flexed to 55 degrees.

13. The movements of hip rotation and elbow extension were sequential. The wrist flexed after the rear foot contacted the court.

14. The weight began on the front foot and moved toward the back fence when the arms were at 45 degrees to the court.

15. The extension of the knees and right elbow, and the flexion of the right wrist did not occur simultaneously at contact.

16. The ball was contacted to the right of and slightly in front of the head. Both feet were off the court. The spine was flexed at an angle of 51 degrees, the upper arm was 60 degrees to the court, and the wrist was 94 degrees to the court.

17. The racquet velocity immediately before contact was 95.50 ft./sec. and was 89.07 ft./sec. after contact.

18. The ball velocity immediately after racquet contact was 92.76 ft./sec. and increased to 96.53 ft./sec. from the third frame to the fifth before decreasing in velocity.

Conclusion

Based on the analysis of the data obtained from the film, and the limitations of the study, the following conclusion was reached. The subject's serve was executed predominately according to the literature. The service motion was smooth with no interruptions and no excess body movements.

The subject did, however, flex her knees before the arms were parallel to the court. Because of this early flexion, the knees were extended and the feet were off the court prior to contact. The subject appeared to flex and extend the knees to obtain what she considered to be optimum use of her body weight and to maximize her height at contact.

Discussion

Plagenhoef (1971) stated that the hand and racquet

decelerated slightly in anticipation of impact. This did not occur during the subject's serve according to the velocity and acceleration graphs. The racquet did decelerate 2 frames before contact according to the tracings. The reason for this discrepancy is not known.

The subject's serve is fast but it is not 'blistering' to the point of being ranked as one of the top serves among professional female tennis players. The subject, at the time of filming, was known more for her doubles play. The first serve in doubles is slightly less powerful because of the need for consistency and the demands of the volley game. To obtain a more powerful serve, the subject might have angled the shoulders upward more than 180 degrees in the backscratch position. The upper arm would not lower with this upward angle in the shoulders, and the front hip would not extend toward the net unnaturally. With this angle of more than 180 degrees, the server would rotate toward the net as well as extending the right shoulder upward to ball contact. The motion of moving the left leg to the rear would pull the weight forward and the left shoulder down. This could accelerate the extension of the right shoulder.

The serve as executed by the subject would be ideal

to teach the beginner and intermediate player. The extent of knee bend would be relative to the skill level of the player. The service motion had the subject reaching upward for the ball instead of chopping it by moving from high to low during contact.

Ball velocity could possibly have been increased if the subject had not reached a full backscratch position. The racquet would cross over the head with the wrist in the flexed position. Instead of continuing downward into the backscratch position, the upper arm would whip around toward the net causing the racquet and forearm to make a loop behind the head. The wrist would become hyperextended during the loop. Before contact, the wrist would extend following elbow extension. This motion possibly would create more velocity through deceleration-acceleration of the upper body link system.

The ball toss was higher than the maximum racquet height so that the subject contacted the ball at full elbow extension even after leaving the court. The ball was contacted after it began to fall. Braden (1977) stated that the ball should be contacted at its peak because by contacting the ball on its way down, the server may slow her motion while waiting for it. The server

should keep the head up until after ball contact, thus preventing, excess flexion of the trunk and loss of power.

The subject did not flex her wrist after contact. By teaching students to flex, the grip may be loosened, thus decreasing the ball's velocity. If the ball is landing outside the court, the student may not be reaching up for the ball. Reaching up for the ball as far as possible means that the only direction the arm can go is toward the net with the racquet head as it goes toward the net and down across the body. This supplies more power to the serve as well as the "snapping" of the elbow before contact.

The use of the trunk, shank, and shoulders is important during the serve. It is necessary that the student utilize these segments during the serve by rotating the body and flexing the knees as described in Chapter IV.

Recommendations for Further Study

The investigator suggests the following for further studies:

1. The use of four cameras that are all set to film at the same frame rate. The fourth camera would film the back of the subject.

2. The use of a top camera that allows the analysis of serves hit to different areas on the court.

3. The comparison of a professional's serve to that of an intermediate club player.

4. The comparison of the tennis serve of a female professional and a male professional.

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