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GROUND REACTION FORCES AND ANKLE AND KNEE MOMENTS DURING ROPE SKIPPING

THESIS

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Ground reaction force (GRF) data collected and synchronized with film data to determine peak GRF and calculate moments about ankle and knee during rope skipping. Two, five minute conditions were analyzed for 10 subjects. Condition 1 was set rate and style. Condition 2 was subjects' own rate and style. Means and standard deviations were reported for peak GRF, ankle and knee moments. One way ANOVAs reported no significant difference between conditions for variables measured. Efficiency and nature of well phased impacts during rope skipping may be determined by combination of GRF, similarities in magnitude and direction of joint moments, and sequencing of segmental movements. Technique and even distribution of force across articulations appear more important than magnitudes of force produced by given styles.

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CHAPTER I

INTRODUCTION

Rope skipping is no longer considered just a child's game or activity. It is seen by some as a good indoor alternative to jogging and other aerobic exercises. Others maintain that its value as an aerobic exercise is exaggerated and that it can lead to ankle and knee injuries due to repetitive impacts with the ground.

Rehabilitation specialists are divided on the issue. It is not unusual to see rope skipping as a part of conditioning programs or in the final stages of an ankle or knee rehabilitation program (Pitreli & O'Shea, 1986; DePalma & Zelko, 1986). Others state that such programs could lead to an injury or re-injury of the ankle or knee joint (Dr. J. Flynt, personal communications, 1985 - 1988).

It is known that a joint is susceptible to injury when the forces and moments acting on that joint exceed the body's ability to manage or dissipate those stresses. There is also a risk of injury if, due to fatigue, the joint's normal mechanics are altered. In biomechanical research, this is determined determined by examining the variables associated with impact. The variables most likely associated with the impact seen in jumping include ground reaction forces, joint forces and moments, and the amount of joint motion at a given point in time. The location of the center of pressure upon the foot may also be a factor.

The research into rope skipping as exercise has mainly addressed the aerobic aspects of the activity. Few of the investigations have addressed the biomechanical aspects. The impact variables, in particular, have received little attention. However, several aspects of impact loading, especially those seen in different forms of jumping, have been examined.

Radin et al. (1973) examined the effects of impulsive loading on the right knee joints of rabbits. The study strongly supported the argument that degenerative arthritis may be the natural consequence of repetitive impulse loadings that are within physiological limits. Cartilage changes were preceded by bony stiffening in every case. The authors also concluded that for joint wear to occur, it is not the total force alone, but its degree and nature that are significant.

Three articles discussed the parameters that take part in the attenuation of the impact forces upon landing from a jump (Coleman, Adrian, & Yamamoto, 1984; Lees, 1981; Mizrahi & Susak, 1982). The correct techniques as well as common errors made in jump landings were presented. The roles of the joint motion and muscle action in the reduction of peak forces during landings were also discussed.

Technique and the influence of the dropping height on the biomechanics of drop jumps were examined in a two-part study by Bobbert, Huijing, and Ingen Schenau (1987a, 1987b). The moments and power output about the ankle and knee joints were influenced by jumping technique but not by the height of the jump.

Valiant and Cavanagh (1985) examined the mechanics of landing from a jump to provide some preliminary design criteria for basketball shoe design. They found differences in landing styles that altered the times and values of the peak impact forces.

In one of the few biomechanical studies into rope skipping, Town, Sol, and Sinning (1980) completed a cinematographical analysis of two subjects to examine the average displacement of the center of gravity and the power values obtained for three predetermined cadences. These limited observations implied that as the rate of skipping increases, the height of the jump decreases with the power values remaining approximately the same.

The relationship between mechanical work done and heart rate and $\dot{V}O_2$ at different cadences using two styles was studied by Routi, Mruk, and Paolone (1980). They concluded that heart rate and $\dot{V}O_2$ were not good indicators of work done while rope skipping.

The bulk of the research examines the aerobic or physiological aspects of the exercise. An early study

(Jones, Squires, & Rodahl, 1962) demonstrated that a significant improvement in physical work capacity, as defined by heart rate and $\dot{V}O_2$ response, could be achieved in a group of untrained individuals using a rope skipping program incorporating alternating exercise and rest periods for a total of five minutes of rope skipping. In 1968, Baker compared rope skipping with jogging. Be concluded that a daily ten minute program of rope skipping was as efficient as a thirty minute daily jogging program for improving cardiovascular efficiency (1968). However, Baker's study was criticized for questionable research design and techniques (Dunn, 1981; Getchell & Cleary, 1980).

The energy cost and heart rate response of rope skipping have been measured by several authors either as single variables or as interacting with other variables (Getchell & Cleary, 1980; Jette, Mongeon, & Routhier, 1979; Myles, Dick, & Jantti, 1981; Quirk & Sinning, 1982; Town, Sol, & Sinning, 1980). At a set rate and style, the energy cost for skipping was 11.9 kcal/min or approximately 66% of the maximum oxygen uptake capacity of the subjects. The heart rates of the subjects averaged between 164 - 167 beats per minute (BPM) (Getchell & Cleary, 1980). When variables of sex, cadence, and style were examined, the energy cost ranged from 8.6 METS with heart rate at 146 BPM at 66 skips/min (Jette, Mongeon, & Routhier, 1979) using two feet skip, rhythm bounce style to 12.5 METS in males at 145 skips/min and heart rate at 184 BPM (Town, Sol, & Sinning, 1980). In one study, females had a lower $\dot{V}O_2$ but higher heart rate values than males (Town, Sol, & Sinning, 1980) while other studies demonstrated no significant sex differences.

Three studies concluded that rope skipping stresses the anaerobic metabolism to a greater degree than other aerobic activities, especially in females. Town, Sol, and Sinning (1980) found mean respiratory quotients greater than 1.0 in both males and females. The mean blood lactates for females reached or exceeded those found for VO_{2max} in the study by Quirk and Sinning (1982), while Jette, Mongeon, and Routhier (1979) found high lactic acid accumulation following skipping.

Statement of the Problem

Rope skipping has been both praised and criticized as an exercise. Many of the physiological components have been addressed and studied. The biomechanical components have had limited study. Impacts from jumping and other weight bearing activities have been examined. The results of such studies help the rehabilitation specialist determine when and which weight bearing exercise should be done. This necessary information for rope skipping is lacking. Therefore, the purpose of this study was to measure ground reaction forces under one foot and compute the net moments about the ankle and knee during different styles and rates of rope skipping in order to establish some baseline data regarding the mechanical aspects of rope skipping.

Delimitations of the Study

The delimitations in this analysis of rope skipping included the following:

1. only one make and style (but not size) of shoe was used;
2. one make of rope from the same manufacturer was used for each trial and subject;
3. only the right extremity was examined.

Limitations of the Study

The limitations in this analysis of rope skipping included:

1. anatomical reference points were approximated;
2. normal limitations inherent in cinematographical analysis were recognized and minimized as much as possible.

Definition of Terms

The following definitions are presented to clarify terms that appear in this text.

1. Rhythm bounce -- A rope skipping style where the subject jumps over the rope as it passes and then performs another, smaller jump as the rope is overhead.

2. Single bounce -- A rope skipping style that is similar to the rhythm bounce, except the subject performs only one jump, with feet together, as the rope passes. There is no second jump.
3. Jogging style -- A rope skipping style where the subject simulates jogging in place, alternating body weight from one leg to the other each time the rope passes underneath.
4. Lower leg -- The portion of the lower extremity distal to the knee joint and proximal to the ankle joint. This medical definition may vary from another discipline's terminology. For example, physical educators may refer to this segment as the calf. In medical terminology, the calf is only the posterior or rear portion of the lower leg segment.

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CHAPTER II

REVIEW OF LITERATURE

> The natural consequence of a jump is the following impact landing. This has received much less attention despite the fact that it is more likely to result in injury (both immediate and long term) as a consequence of the large impact forces (Lees, 1981, p. 207).

Some variables associated with impact landings seen in jumping include ground reaction forces, joint forces and moments, and the joint angles at a given point in time. These variables have not been examined for rope skipping. Therefore, whether the stresses placed on the lower extremity during rope skipping exceed the body's ability to dissipate those stresses is unknown.

This factor, as well as the aerobic demands placed upon the body, is debated in the clinic and in the literature. Rope skipping programs are a part of rehabilitation, athletic conditioning, and aerobic exercise programs. DePalma and Zelko (1986) presented a rehabilitation program to be used following anterior cruciate ligament injury and/or surgery. Their 12 phase program based on "research, practical experience, and strength and power lifting principles" (p. 200) includes rope skipping as a part of Phases IX and X.

It is performed three days per week along with jogging, swimming, and cycling.

Pitreli and O'Shea (1986) applied rope skipping to athletic conditioning programs. It acts as a supplementary or complementary role with other seasonal training programs. It can be used for pre-season, in-season, and off-season training. The authors maintain that rope skipping can also be used as a metabolic warm-up and cool-down between sets in a weight training regimen. The authors present tables that outline suggested rope jumping programs for basketball, football, and volleyball.

The American Heart Association (AHA) advocates rope skipping as exercise. In 1983, the AHA published a jump rope guide entitled Jump for the Health of It. The guide details the benefits of jumping rope, equipment needed, teaching suggestions, and stunt descriptions. The cited benefits include:

1. it is a good aerobic activity;
2. provides a conditioning program to achieve a training effect;
3. improves fine and gross motor coordination as well as timing and speed;
4. helps in tension relief and aids relaxation and sleep;
5. enhances self esteem and promotes a positive

body image;

6. serves as a foundation for sports skills; and,
7. develops an opportunity for creativity.

The guide states that rope skipping can be an indoor or outdoor activity for all ages and requires little space and equipment. Rapid progression can be achieved resulting in immediate satisfaction.

The kinematics and kinetics of rope skipping have not been addressed in as much detail as the physiological aspects, which dominates the bulk of the available literature into the activity. Impact as applied to the repetitive jumping action has received little attention. However, several studies have sought to explore the nature of impact and repetitive loading especially in different forms of jumping.

There is evidence to suggest that repetitive impulse loading may be a factor in the development of degenerative joint arthritis. Radin et al., (1973) subjected the right lower extremity of male, white New Zealand rabbits to impulse loading approximately equivalent to their body weight at a rate of 60 times per minute for one hour daily. During the time of loading, the hind legs were held in maximum knee extension by a methylmetracrylate splint. The dynamic force was applied to the right lower extremity by a motor driven cam. The left lower extremity was not attached to the cam, serving as a control. There was no apparent discomfort to the rabbits and except for one hour spent in the harness used for the loading, the rabbits were free to roam in their cages at will.

The rabbits were sacrificed by twos at two-day intervals up to 30 days and again at 36 days. The knees were then disarticulated and readied for study mechanically and anatomically.

The right knee joints of the rabbits developed changes consistent with the development of degenerative arthritis. Bony stiffening of the underlying subchondral bone preceded cartilage changes in every case. Incidence of trabecular microfracture in various states of healing was found in the right knee joints more so than in the control joints.

The authors concluded that the results strongly support the idea that joint degeneration can be a consequence of repetitive impulsive loading within physiological limits. The degree and nature of the force, not the total force alone, appears to be significant.

In the previous study, the rabbits' knees were kept in full extension. They were not allowed to attempt to dissipate the impact forces. The parameters that take part in the attenuation of the impact forces upon landing from a jump have been presented by several authors. Mizrahi and Susak (1982) examined four parameters of impact forces on the legs during a vertical landing in different falling conditions. These conditions included (a) body position during landing,

(b) range of joint flexion at impact, (c) usage of ground-roll immediately after impact, and (d) softness of the ground.

Two female and three male instructors of physical training performed a number of falls from .5 m and 1 m heights. Landings from the lower height were split so that three landings were made on the balls of the feet and three were made flat-footed. Four jumps were made from the higher height, landing on the balls of the feet. Two of the 4 jumps were performed with a lateral ground roll. Soft landings were done by two subjects using 5 cm thick foam rubber sheets.

The force curves for all landings demonstrated two peaks. The force intensity was characterized in all landings by these two peaks. At the .5 m height, the flatfoot landing style had very large initial peak forces that were generally greater than the ball of foot landing. The ball of foot landings had a range of 3.78 - 4.77 body weight (BW). The flatfoot landings recorded 2.47 - 6.55 BW. Both peaks in the 1 m jump demonstrated an increase in intensity compared to the ball of foot landings in the .5 m jumps. However, the peaks recorded flatfooted at the .5 m height were greater than the first peak of the ball of foot landings at the 1 m height. The range for the flatfooted peaks was 2.98 - 5.6 BW. The ground roll and soft landing styles decreased both peaks of force. The flexion range of motion of the lower extremities were generally bigger from the higher jump.

The authors concluded that a ball of foot landing decreases the peak forces when compared with flatfoot landings. Increased range of joint motion and muscle action during the early phase of impact proved important in reducing peak forces. The simultaneous use of proper coordination between joints as seen in the ground roll help to decrease landing peak forces. The quality of the ground and shoes worn by subjects demonstrated in the soft landings also play roles in peak force attenuation.

Valiant and Cavanagh (1985) found similar patterns of landing when landing forefoot versus flatfoot. They examined ten male intramural basketball players rebounding a basketball dropped from a random orientation above their heads. Force recordings were taken only under the right foot.

The forefoot landing style showed two peaks, but in the flatfoot style, the first peak was absent. In the forefoot landing group, the first peak ground reaction force averaged 1.3 BW with a second mean peak of 4.1 BW with a mean time-to-peak duration of 37 ms. The flatfoot group averaged a peak vertical force of 6.0 BW occurring at 12 ms. In applying this information to shoe design, the authors suggested that both landing styles be addressed.

Correct technique and errors encountered in jump landings were addressed by Coleman, Adrian, and Yamamoto (1984). They devised an equation that could calculate the minimum landing force that could be expected from any landing. The equation defines the minimum peak force as body weight times the ratio of the falling distance to the cushioning distance.

Athletes stepped off a box 24 inches high and were instructed to land as softly as possible. With a 12 inch cushioning distance, the predicted minimum force was 2 BW. However, the calculated values were 3 to 4 times body weight with the minimum value at 2.25 BW.

The correct technique for landing was described as a soft, cushioned landing with the body segments in proper alignment. "The stable position includes full foot contact with the floor, legs flexed with knees over toes, hips in skeletal locked position, and trunk muscles tightened to produce the normal, slightly curved lumbar spine." (p. 197)

The common errors found by the authors resulting in higher peak forces than predicted included:

1. ball of foot stabilization instead of full foot;
2. knees in valgus position with feet pronated and everted;
3. force of landing not shared equally by each leg;
4. excessive hip and knee flexion; and
5. spinal flexion instead of spinal extension.

Lees (1981) further described landings from a jump as "soft" or "hard" depending on the relative magnitudes of the vertical component of the initial force peak. Impact absorption lasts for only 150 - 200 ms of the full landing action. The hard landing is characterized by a high magnitude of negative acceleration of the two leg segments immediately after impact. This is indicative of the stabilizing effects of the muscles surrounding the joint. With such stabilization, a rapid, large positive acceleration then occurs. The acceleration is transferred to the other segments, the thigh, trunk, and head.

In the soft landings, the negative acceleration of the segments is generally lower and extends over a longer period of time, indicating a better preparation and control exerted by the joint musculature. The landing is produced by phased deceleration of the segments with a pattern of muscle activity that anticipates the demands made upon it.

Bobbert, Huijing, and Ingen Schenau (1987a, 1987b) performed a two-part study examining first the influence of technique and secondly, the influence of dropping height on the biomechanics of drop jumping. In the first study, 10 male volleyball players performed two jumps from a 20 cm height for each of two styles of drop jumping: (a) bounce drop jump, and (b) countermovement drop jump. In the bounce drop jump, the subject tries to change the direction of the movement as soon as possible after landing. In the countermovement drop jump, the reversal of direction is slower with some cushioning effect added. They also performed a countermovement jump from ground level. The height jumped was defined as the difference between the highest position reached by the body's center of mass (CM) and the position of the CM in upright standing.

Large differences in time during which the CM of the body was accelerating upwards during push-off were observed. However, only slight differences were found in the vertical velocity of the CM. The moments about the knee and ankle were larger in the bounce drop jump than in the countermovement drop jump. The moments in both drop jumps were greater than in the countermovement jump. The hip and knee angles were also greater in the bounce drop jump than in the countermovement drop jump. Again, the countermovement jump results were less than the drop jumps.

The authors concluded that the mechanical output about the ankle and knee joints was enhanced in the execution of the drop jumps over and above that seen in the countermovement jump. This enhancement depends on the jumping technique with the bounce drop jump reaching larger moments and power output values than the countermovement drop jump.

The second study used six males trained in drop jumping techniques. The subjects jumped from heights of 20, 40, and 60 cm using the bounce drop jump technique. There were no differences found in the vertical jumping achievement between the jumps executed from different heights. The moments and power output about the knee and ankle joints during push-off did not increase. Due to sharp, high intensity force peak at impact at the 60 cm height, the authors could not see any advantage of performing bounce drop jumps from that height.

There are few biomechanical studies specific to rope skipping. A limited cinematographical study was done by Town, Sol, and Sinning (1980) on two of the subjects from their physiological study. The subjects were filmed at each rate at 64 frames/second from which the average excursion of the center of gravity for each skip, total vertical displacement, and the work rate were determined. The rate of work (power) was similar for all skipping rates for each subject. As the skipping rate increased, the center of gravity displacement decreased.

Routi, Mruk, and Paolone (1980) examined the relationship between work (W), heart rate, and $\dot{V}O_2$ during two minutes of rope skipping using two styles at rates of 80, 100, and 120 skips/min. Mean values of W for the double-footed style ranged from 12,066 ft.lbs to 19,020 ft.lbs. The alternate-foot style values were 11,329 - 17,170 ft.lbs. The values for heart rate and $\dot{V}O_2$ compared to those found by the other authors. There was no significant difference between $\dot{V}O_2$ and W at any rate for either style. There was a significant relationship between W and heart rate for the double-footed style, rate 80 skips/min and the alternate-footed style, all three rates.

The aerobic aspect of rope skipping has received the most attention in the literature. Jones, Squires, and Rodahl

(1962) examined the effect of a rope skipping program on physical work capacity using seven untrained women, ages 19-42. The physical work capacity of each subject was assessed before and after the 4 week training period using heart rate response to submaximal work loads on a bicycle ergometer. The maximal oxygen uptake was estimated according to the Astrand nomogram.

The rope skipping program consisted of skipping one minute, resting two minutes, skipping one minute, etc. for a total of five minutes rope skipping and ten minutes rest, Monday through Friday, for four weeks.

The results showed a 25% improvement in estimated VO_{2max}. A control group of three untrained women within the same age limits showed no change in heart rate and $\dot{V}O_2$, leading to the conclusion that significant improvement in physical work capacity can be achieved in untrained individuals as the result of the defined program.

Baker (1968) used 22 male college students to determine the effects upon cardiovascular fitness that resulted from programs of jogging and rope skipping. The subjects were randomly divided into two groups. Group I skipped rope for 10 min/day, 5 days/week for 6 weeks. Group II jogged 30 min/day, 5 days/week for 6 weeks. The Harvard step test was administered to each subject before and after the conditioning programs. As there was no significant difference between the groups at either the start or the end of the program, Baker concluded that:

1. a daily 10 minute program of rope skipping will improve cardiovascular efficiency;
2. a daily 30 minute program of jogging will improve cardiovascular efficiency;
3. ten minutes of daily rope skipping are as efficient as 30 minutes of daily jogging for improving cardiovascular efficiency.

Baker's study has undergone criticism for questionable research design and technique (Dunn, 1981; Getchell & Cleary, 1980). Baker did not have a nonexercising control group for comparison and did not attempt to ensure that both groups exercised at the same intensity. The Harvard step test measures cardiovascular efficiency on the basis of heart rate recovery from submaximal exercise. Using such a method to issue conclusions regarding training effects is considered "experimentally risky" and open to "considerable chance for error" (Getchell & Cleary, 1980, p. 56).

Several researchers have examined the energy cost and heart rate response of rope skipping. Their findings are summarized in Table 1.

Table 1

Summary of Energy Cost and Heart Rate Responses

Author(s)	Mean Energy Cost (METS)		Mean Heart Rate Response[a]	
	Male	Female	Male	Female
Myles et al.			140 - 166[b]	
Getchell & Cleary	10.8	6.6	161	180
Jette et al.	8.6 - 11.9[b]		146 - 176[b]	
Town et al.	11.7-12.5	11.7-11.8	172-174	176-177
Quirk & Sinning	10.9-12.7	11.3-11.4	166-178	181

[a]BPM

[b]Did not distinguish between sexes

Myles, Dick, and Jantti (1981) used 6 subjects to compare the exercise intensity, as estimated by heart rate, of six commonly used skipping styles and to determine whether any of the styles could be recommended as the basis for a training program. The six styles were the hop, leap, jump, rhythm jump, rhythm hop, and rhythm leap. The subjects skipped at their own pace for 2 minutes each style, completing 3 two-minute sessions per day. The heart rates and skipping rates for the 3 rhythm styles were lower than the other 3 styles. All the subjects complained of pain and discomfort during the jump style. Using either the rhythm hop or rhythm leap, all subjects were able to skip continuously for at least 10 minutes. Heart rates rose rapidly to about 140 BPM within the first minute. The authors suggested that for individuals up to middle age, the rhythm hop and rhythm leap may be recommended for a training program.

The energy cost and heart rate response to rope skipping were measured and related to comparable intensities of jogging by Getchell and Cleary (1980). Seven males and 3 females used a special apparatus which provided a means for the collection of respiratory gases while smoothly skipping. Each subject performed two-footed skipping with a rebound at 80 rpm for 6.5 minutes. To determine the energy cost of running, respiratory gases were collected while each subject ran on a treadmill at a speed and grade that most nearly elicited their heart rate response to rope skipping. The energy cost for rope skipping during the last minute of each bout was approximately 66% of the maximal oxygen uptake compared to 74% found on the treadmill, leading to a precautionary statement that skipping rope is not reasonable as a mode of fitness for an average sedentary person.

The energy cost of different intensities of rope skipping was examined by Jette, Mongeon, and Routhier (1979). Five subjects skipped at the required pace for the first 2 minutes of a 5 minute skipping bout. Expired air was collected for 30 seconds during the next minute while the subject held the cord in one hand and simulated skipping. Sitting, standing, and exercise $\dot{V}O_2$ were determined by the open-circuit method. Maximal oxygen uptake was determined on the treadmill. One cc of venous blood was drawn at rest at 3 minutes following selected skipping intensities for lactate analysis. The skipping intensities were:

Level A: 66 turns/min; one foot skip, plain bounce
Level B: 66 turns/min; one foot skip, rhythm bounce
Level C: 66 turns/min; two feet skip, plain bounce
Level D: 66 turns/min; two feet skip, rhythm bounce
Level E: 84 turns/min; two feet skip, plain bounce
Level F: 102 turns/min; two feet skip, plain bounce
Level G: 120 turns/min; two feet skip, plain bounce
Level H: 132 turns/min; two feet skip, plain bounce.

The net energy expenditures of the various modes of skipping were similar except for levels D and F. Level F was the most demanding at 11.9 METS with a heart rate response of 88% of the mean maximal heart rate induced on the treadmill. Level D was the least demanding at 8.6 METS and 73% of maximum. A significant difference was found only between these two levels. The heart rate achieved its peak level by the fourth minute of the bout. Again, the authors observed that a rope skipping program designed to be equivalent in energy cost to jogging was hardly feasible for the average, sedentary person. To expend the same energy as jogging 3 miles in 30 minutes, an individual would be required to skip 33.8 minutes at level D or 24.9 minutes at level F.

Two studies were done at the Applied Physiology Research Laboratory at Kent State University. The first study (Town, Sol, & Sinning, 1980) evaluated the energy cost and any sex differences found in response to rope skipping. Eleven females and 19 males, all physically active, used an apparatus for gas collection while skipping similar to the apparatus designed by Getchell and Cleary (1980). The subjects skipped for 5 minutes at 1 of 3 predetermined cadences, 125, 135, and 145 turns/min, jumping once per turn. Significant differences due to sex were found for $\dot{V}O_2$, heart rate, $\dot{V}_E$, and energy expenditure. There was no significant difference found between rate and sex. With MET values between 11.7 and 12.5 METS, the authors also suggested that rope skipping is a strenuous exercise.

Quirk and Sinning (1982) conducted another study to further examine sex differences in response to skipping, the equality of $\dot{V}O_2$ at different rates and the role of the anaerobic metabolism. Six male and female college students skipped rope at 120, 140, and 160 skips/min for 5 minutes. VO_{2max} and $VO_{2debtmax}$ were determined from inspired and expired air taken at rest, during maximal bicycle ergometer test, and from a 15 minute post-exercise period. The test protocol was the same as for the previous study. For lactate analysis, a sample of blood was drawn 5 minutes after exercise for both the bike and rope skipping tests. Again, there was no difference between rate and VO_{2max}. Significant differences were found due to treatment and interaction but not sex. The males had a higher $\dot{V}O_2$ for the max test than for any of the rope skipping treatments. Their $\dot{V}O_2$ at 160 skips/min were significantly higher than at 120 and 140 skips/min. Post hoc tests did not show any significant differences among treatments for females. The heart rate response was significant for sex, treatment, and interaction.

The 3 previous studies all suggested that rope skipping is a strenuous exercise. They also agree that the activity stresses the anaerobic metabolism. The mean respiratory quotients in the study by Town, Sol, and Sinning (1980) were all greater than 1.0 indicating an anaerobic source for some of the energy expended. Blood lactate levels were found to be 7.4 mM/l for males at 120 skips/min to 12.0 mM/l for females at 140 skips/min in the study by Quirk and Sinning (1982) and 1.32 mM/l at 66 turns/min at level D to 12.2 mM/l at 102 turns/min. level F, in the study by Jette, Mongeon, and Routhier (1979). Females had significantly higher levels at 120 and 140 turns/min, but no significant difference at 160 turns/min. These mean values for females reached or exceeded those found after VO_{2max} while the males attained levels to that 79-87% of the bicycle maximum.

Most of the research into rope skipping has addressed the physiological aspects of the activity. Some authors infer that rope skipping is an effective aerobic exercise with more benefits and advantages than other aerobic exercises. Still other researchers suggest that rope skipping is a strenuous exercise that may not be suitable as a training program for achieving cardiovascular fitness. Although the nature of impact loading has been examined for other forms of jumping, it has not been examined for rope skipping. The few biomechanical studies available address displacement and work done during the activity. Other mechanical considerations, such as the amount and nature of impact loading on the lower extremity have not been examined.

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CHAPTER III

PROCEDURES

The purpose of this study was to measure ground reaction forces under one foot and compute the net moments about the ankle and knee during different styles and rates of rope skipping. The procedures for the collection and analysis of data are presented in this chapter.

Subjects

Eight males and 2 females from the Denton - Dallas - Fort Worth Metroplex region in Texas acted as subjects. The demographic data, including means and standard deviations, for the subjects are presented in Table 2. Informed consent was obtained from each subject (See Appendix A). The subjects were experienced rope skippers. Experience in this context meant that the subjects had used rope skipping as an aerobic exercise or for fitness training either prior to, or at the time of testing. They also fulfilled the following requirements:

1. were able to maintain a skipping for two, 5 minute sessions;
2. accustomed to wearing the shoe size(s) used in this study;

3. had no lower limb pain or discomfort at the time of the testing sessions.

Table 2

Demographic Data of Subjects with Means and Standard Deviations

Subject #	Weight (kg)	Height (cm)	Age
1	64.5	177.4	21
2	72.73	175.1	18
3	75.57	175.3	31
4	81.36	169.75	41
5[a]	50.5	163.0	32
6	74.5	177.4	31
7	76.91	180.4	39
8	86.0	189.3	26
9	84.55	173.4	33
10[a]	71.0	174.0	27
Mean	73.762	175.505	29.9
S. D.	±10.399	±6.8137	±7.203

[a]Females

Instrumentation

Force Measurement

The ground reaction forces and their points of application were measured with a Kistler Force Plate (Amherst, N. Y.). The force plate was interfaced with an eight channel amplifier connected to an analog-to-digital (A/D) converter interfaced with an Apple IIe microcomputer.

Cinematography

Two cameras were used for this study. A Locam 16mm high speed movie camera (Model 51, Redlake, Ca.) was used for a frame-by-frame analysis of the sagittal view in this two-dimensional study. The camera was level on a platform approximately 60 feet from the force plate. Spatial and temporal references were in field of view as were coded cards for subject identification and condition number. The second camera, a Photosonics 16mm high speed camera (Model PN61-1400, Burbank, Ca.) was placed for a frontal view aimed at the subjects' feet. This was to verify that the subjects' right feet hit the target area on the force plate. The target area of the force plate was marked inside the edges of the force plate. If the foot landed outside the target area, the forces and center of pressure readings were considered to be inaccurate and the data was considered bad data and was not used in the analysis of the results. Figure 1 depicts the collection area.

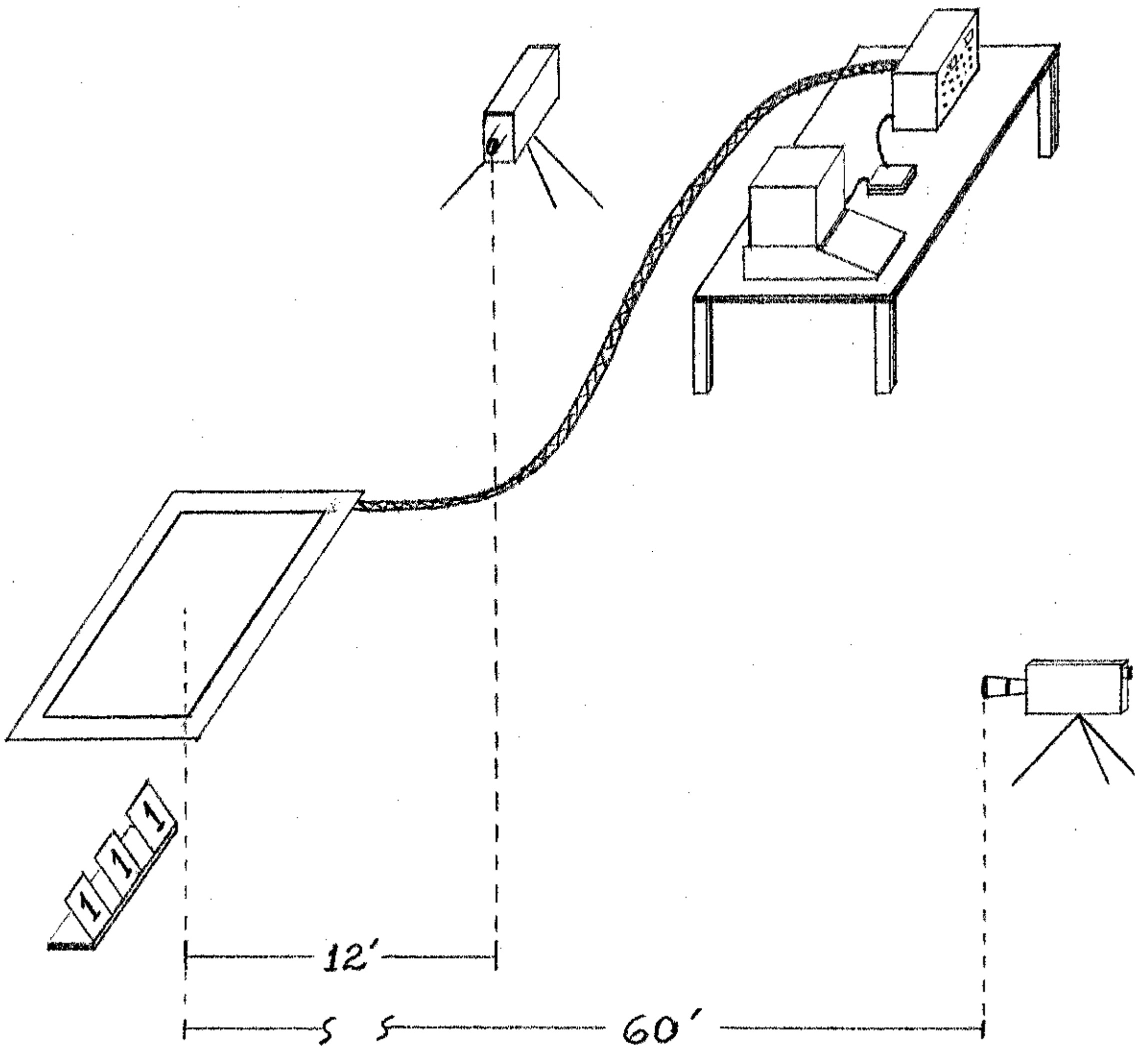

Fig. 1. Collection Area

Jump Rope

Lifeline jump ropes (Madison, Wi.) fitted to each subject were used.

Testing Procedures

All data collection was done at the Physical Education complex of Texas Woman's University, Denton, Texas.

Force Plate Calibration

All instrumentation was calibrated before each testing session. The force plate was calibrated using the technique established by Dr. Jerry Wilkerson of the Biomechanics laboratory at Texas Woman's University. For the vertical axis, a known weight was placed just inside the four corners and in the center. The results were viewed on the computer monitor and recorded. The force plate was considered to be correctly calibrated if the four z-coordinate values were consistent with the known weight and the center reflected the known value of the center of pressure. For the horizontal axes, a known weight was suspended across the force plate along each axis by a wire adhered to a clamp that is attached to the force plate. The weight was lifted for resetting the force plate, then lowered and the results recorded and compared. The calibration was acceptable if the direction and magnitude of x_1 and x_2 were consistent with each other. The same was true for the two y channels. This check was done prior and after that day's usage as temperature and humidity may alter the unit readings on the force plate.

Anthropometric Measurements

Anthropometric measurements of subjects were taken at the time of data collection. Body weight was taken on a balance scale and converted to body mass in kilograms. The segment lengths measured, in centimeters, are listed and defined as:

1. foot segment--posterior end of calcaneus to the tip of the longest toe along the sole of the foot;
2. lateral malleolus height--floor to lateral malleolus;
3. lower leg segment--estimated joint center of knee to lateral malleolus;
4. thigh segment--greater trochanter to estimated joint center of knee.

The anatomical reference points of the right ankle, knee, and thigh, necessary in making various computations, were marked with flexible white tape, 3M microfoam, adhered to the skin circumferencing the joint but allowing for unrestricted motion of the joint. The tape was marked in the center with a black line (See Figure 2).

Data Collection

All subjects were given ample time to warm-up and familiarize themselves with the testing surface and test

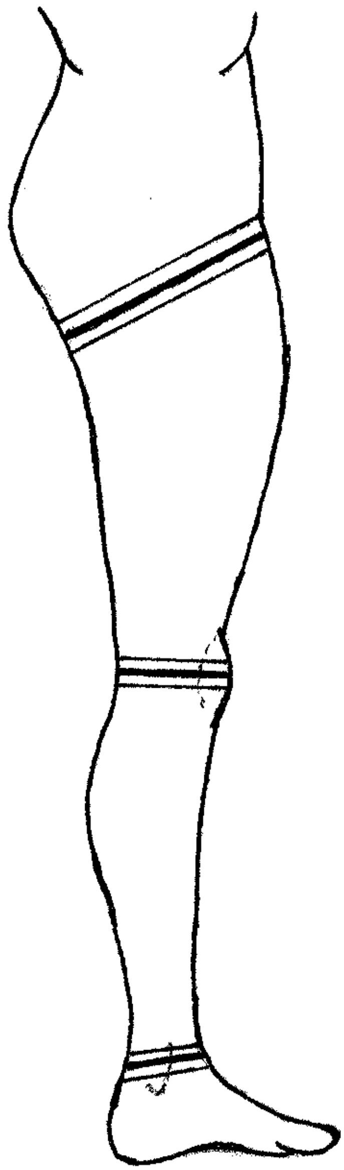

Fig. 2. Anatomical Reference Points

styles and cadences that were employed. The order of testing for both conditions and placement within the condition was determined randomly. The random numbers were generated using the RND function of the Apple IIe computer.

Two conditions of rope skipping were used in this study. They were (a) 80 turns/min, 2 feet rhythm bounce, and (b) subjects' own style and rate. The rhythm bounce was defined as having the subjects jump over the rope as it passed, and then perform another, smaller jump as the rope was overhead. A metronome was used to keep cadence of the set rate. Each condition was performed for 5 minutes with adequate rest in between each condition. The amount of rest was from 10 - 25 minutes based on the subjects' resting heart rate and their perception of fatigue (verbal only). The second session resting heart rate had to be within 10 BPM of the first session resting heart rate.

Filming and samplings off the force plate were taken at the end of the fifth minute for a duration that was long enough to record 3 weight-bearing events on the force plate (approximately 4 seconds). The sampling rate off the force plate was 536 Hz. The timing between the force plate and the filming was synchronized using a strobe. The strobe was engaged at the moment the computer started reading force samples. Both the strobe and the computer were started manually. This system was doublechecked using a second method. The time of the airborne phase of the skip can be determined from both the film and the force plate. The known time of this phase was used to synchronize the timing of the ground phase. The nominal camera frame rate was approximately 100 frames per second (fps).

Data Analysis

A multistep process was used to calculate the moments about the ankle and knee joints. The process involved (a) obtaining and smoothing raw data from film, (b) manipulating that data to compute segmental and joint kinematics, and (c) combining the film data and force plate data to finally calculate the moments about the joints.

Mathematical Model

The lower extremity was modeled as three rigid segments. The thigh and lower leg segments were each represented as a thin rod with the longitudinal axis running through the center of mass from the proximal joint axis to the distal joint axis. The foot segment was defined as a triangle with lines connecting the various landmarks as follows: (a) a line running from the posterior aspect of the calcaneus to the tip of the longest toe along the sole of the foot, (b) a line between the height of the lateral malleolus and the tip of the longest toe, and (c) a line connecting the calcaneus to the lateral malleolus (See Figure 3).

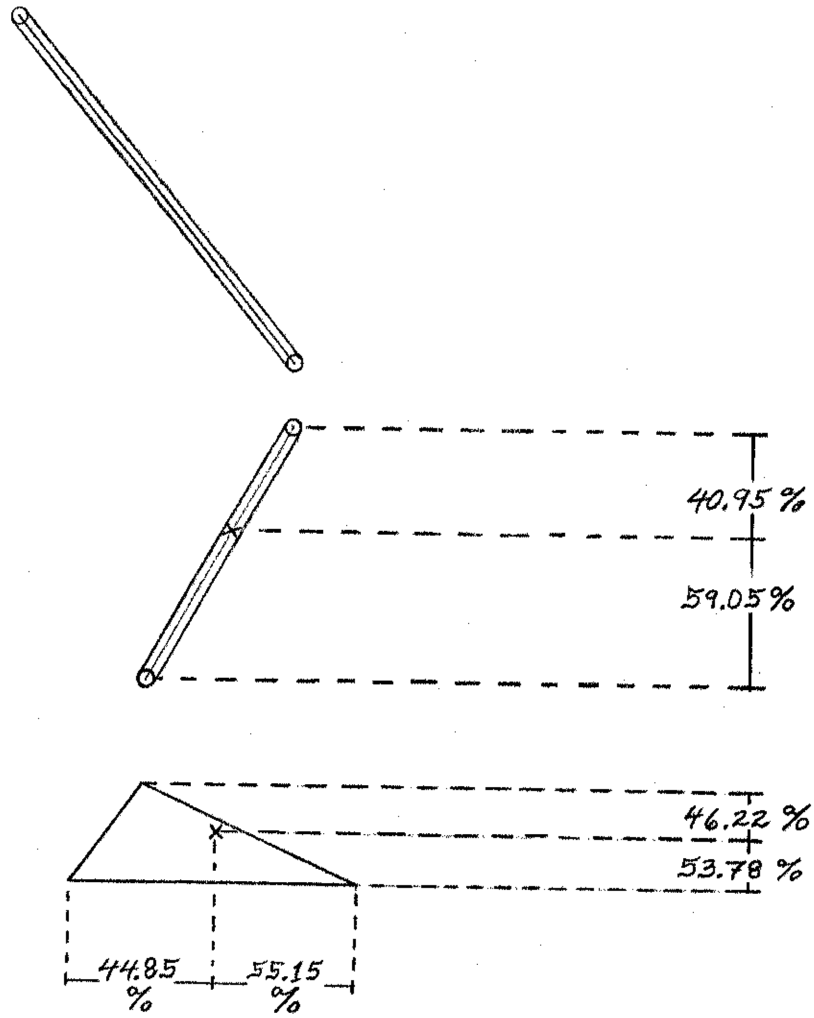

Fig. 3. Mathematical Model

Body Segment Parameters

In the calculations discussed later in this chapter, known values for the center of mass location, segment mass determination, and the moment of inertia for the segments of interest were used. The location of the segments' center of mass was expressed as a percentage of the total distance between the proximal and distal reference points. The segment mass was related to the total body mass as a proportion of that mass. The moment of inertia given was about a transverse axis through the segment center of mass. The thigh segment was included to calculate the knee angle only. Therefore, no body segment parameters were needed for the thigh segment. Table 3 presents the values used by this study.

Digitizing Procedure

Film was projected frame-by-frame onto a digitizing table. The x and y coordinates of 6 points were digitized off each projected frame using a Numonics digitizer (Model 1220, Lansdale, Pa.) interfaced with a Tektronics computer (Model 4052, Beaverton, Or.). The 6 points were:

1. hip joint center,
2. knee joint center,
3. ankle axis (lateral malleolus),
4. heel,
5. tip of longest toe, and
6. reference point, constant for each frame of film.

Table 3

Body Segment Parameters

Segment	Center of Mass Location	Segment Mass Proportion[a]	I[b] (kg.m^2)
Lower leg	40.95% to knee axis[c]	0.0435	0.0505
Foot	44.85% of heel/ foot length, and 53.78% sole to lateral malleolus height[a]	0.0147	0.0038

[a]Clauser, McConville, and Young (1969) mean data

[b]Whitsett (1963) mean data

[c]Hinrichs (1982) mean conversion data correction to Clauser, McConville, and Young mean data

One known reference length was filmed at the beginning of each time of data collection and film change, and its coordinates digitized to provide a scaling factor of the digitized-to-actual length. At the same time, reference markers placed on the force plate to define the x-y lengths and orientation were filmed for use later in converting force plate center of pressure coordinates to digitized center of pressure coordinates.

The reference point was subtracted from all segment points to provide a consistent two-dimensional reference. Subsequent manipulation of the coordinates was then accomplished using the same (x,y) coordinate system with the origin at (0,0). Also at this time, the digitized lengths were converted to actual lengths by multiplying the digitized lengths by the scaling factor. The calculated actual segment length was compared to the anthropometric measurement of the segment length as a check.

Smoothing

Prior to data manipulation, the raw data obtained from the digitizing procedure was smoothed to minimize digitizing errors. The quintic spline method for smoothing data was used (Wood, 1982).

Kinematics

Data manipulation began with describing the motion of the segments. This was done in terms of the linear and angular acceleration of the segments.

Linear Acceleration

The linear acceleration needed was the acceleration of the segment at its center of mass, not at the joints. The components of this acceleration (a_x,a_y) were calculated from the digitized data.

Center of mass location

First, a method was needed to locate the center of mass of each of the segments. As previously mentioned, the digitized points represent a proximal-distal reference of the segment. Examining Figure 4, the segment long axis vector is represented by the vector $\vec{S}_{D/P}$ which is defined by

$$\vec{S}_{D/P} = \vec{S}_D - \vec{S}_P$$

where $\vec{S}_D$ is the vector from the distal end of the segment relative to the origin and $\vec{S}_P$ is the vector from the proximal end of the segment to the origin. The center of mass location is located along $\vec{S}_{D/P}$ at some proportional distance, γ (given in Table 3), for each segment from the proximal/distal reference points as denoted by

$$\vec{S}_{C/P} = \gamma \vec{S}_{D/P}$$

where $\vec{S}_C$ is the vector locating the center of mass relative to the proximal end of the segment. Through vector addition

$$\vec{S}_C = \vec{S}_P + \vec{S}_{C/P}$$

where $\vec{S}_C$ is the vector locating the center of mass relative to the origin. Substituting for $\vec{S}_{C/P}$, the equation now

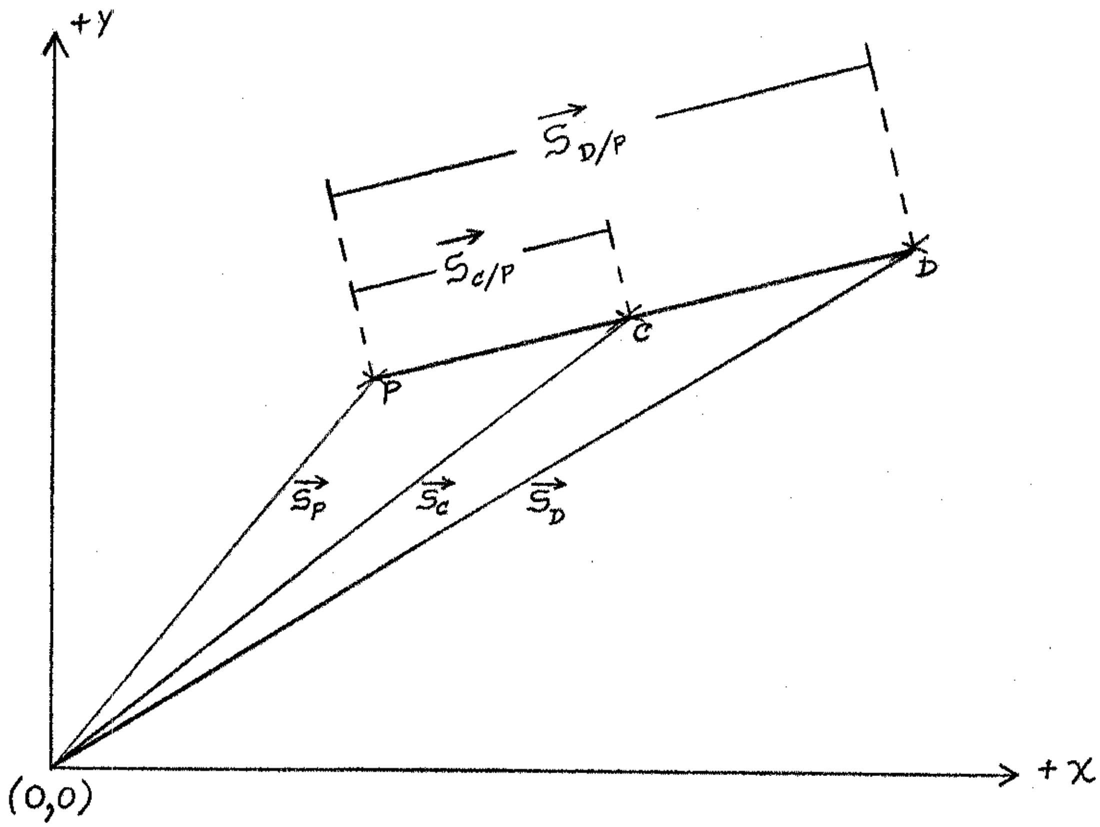

Fig. 4. Center of mass location

becomes

$$\vec{S}_C = \vec{S}_P + \gamma \vec{S}_{D/P}$$

$$\vec{S}_C = \vec{S}_P + \gamma (\vec{S}_D - \vec{S}_P) \qquad (1)$$

As the center of mass point of the segment moves from one location to another, the linear motion can be described by the displacement the point undergoes as a function of time. As that time interval becomes very small, the acceleration of the center of mass point (r) is the second derivative of the displacement. Thus,

$$\vec{a}(t) = \frac{d^2\vec{r}}{dt_2}.$$

The component accelerations (a_x, a_y) for each segment center of mass was thus calculated from

$$a_x(t) = \frac{d^2 r_x}{dt^2} \qquad (2)$$

$$a_y(t) = \frac{d^2 r_y}{dt^2} \qquad (3)$$

The quintic spline functions were analytically differentiated to compute the acceleration.

Angular Acceleration

Calculation of the angular acceleration (α) was similar to the process for finding the linear acceleration except the angular acceleration describes the angular motion of the entire segment, rather than the linear motion of its center of mass.

Again, the proximal and distal digitized points (P and D) acted as the reference points for the segment as it moved in the x-y plane (See Figure 5). At time t_1, the segment was in configuration I. At time t_2, it was in configuration II.

The orientation of the segment long axis, $S_{D1/P1}$, was defined by angle θ_1, such that

$$\theta_1 = \tan^{-1} (a/b) \qquad (4)$$

where

$$a = D_{1y} - P_{1y}$$

$$b = D_{1x} - P_{1x}.$$

Similarly, the angle θ_2 was defined such that

$$\theta_2 = \tan^{-1} (c/d) \qquad (5)$$

where

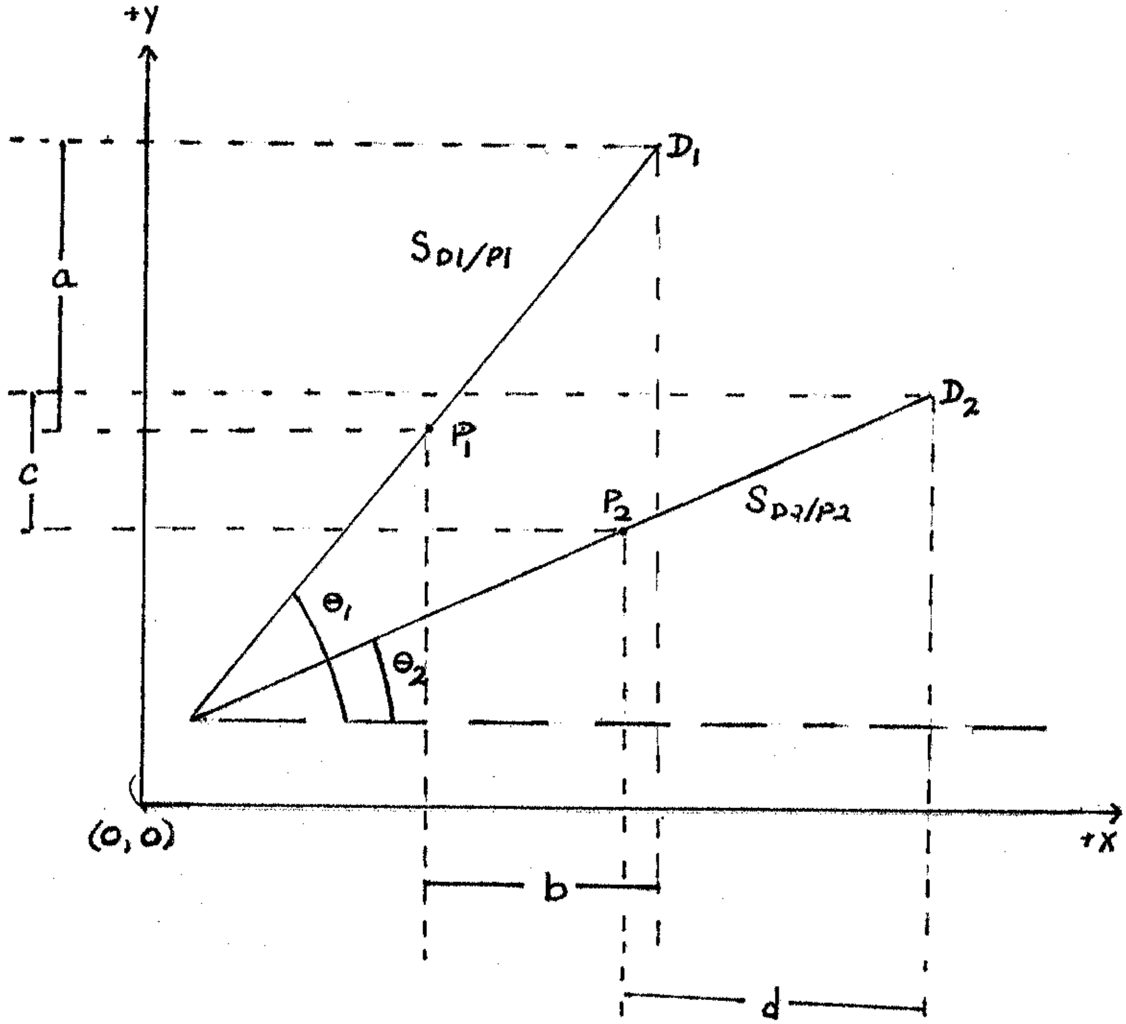

Fig. 5. Segment angle determination

$$c = D_{2y} - P_{2y}$$

$$d = D_{2x} - P_{2x}.$$

However, one check was made. By convention, all angles are measured in the counterclockwise direction starting with the positive horizontal being equal $0°$. It is then divided into 4 quadrants.

Equations 4 and 5 work only in quadrants I and IV where

$$-90° \leq \theta \leq 90°$$

The inverse tangent does not provide for angles found in quadrants II and III. The coordinates of the points in the quadrants follow this pattern:

Quadrant I (+x,+y)
Quadrant II (-x,+y)
Quadrant III (-x,-y)
Quadrant IV (+x,-y)

For the digitized coordinates that fit the pattern for quadrants II and III, the angle of the segment was computed by adding $180°$ to the angles computed in equations 4 and 5.

The angular acceleration, α, is the second derivative of the angular displacement. Thus,

$$\alpha(t) = \frac{d^2\theta}{dt^2} \qquad (6)$$

As for linear acceleration, the quintic spline functions were analytically differentiated to compute the angular acceleration.

<u>Segment Angle vs Joint Angle</u>

The angles calculated to find the segment angular acceleration are not to be confused with the joint angles. The joint angles were determined for descriptive purposes by the locations of the articulating segment angles. Full extension of the knee is defined by 0° flexion where from Figure 6

$$\Theta_k = \Theta_{21} - \Theta_{32}$$

If $\Theta_{21} > \Theta_{32}$ the knee was flexed.
If $\Theta_{21} < \Theta_{32}$ the knee was extended.

The ankle angle, Θ_a, was defined by

$$\Theta_a = \Theta_{32} - \Theta_{54} + 90^\circ$$

If Θ_a was positive, the foot was plantarflexed.
If Θ_a was negative, the foot was dorsiflexed.
If Θ_a equaled zero, the foot was in neutral position.

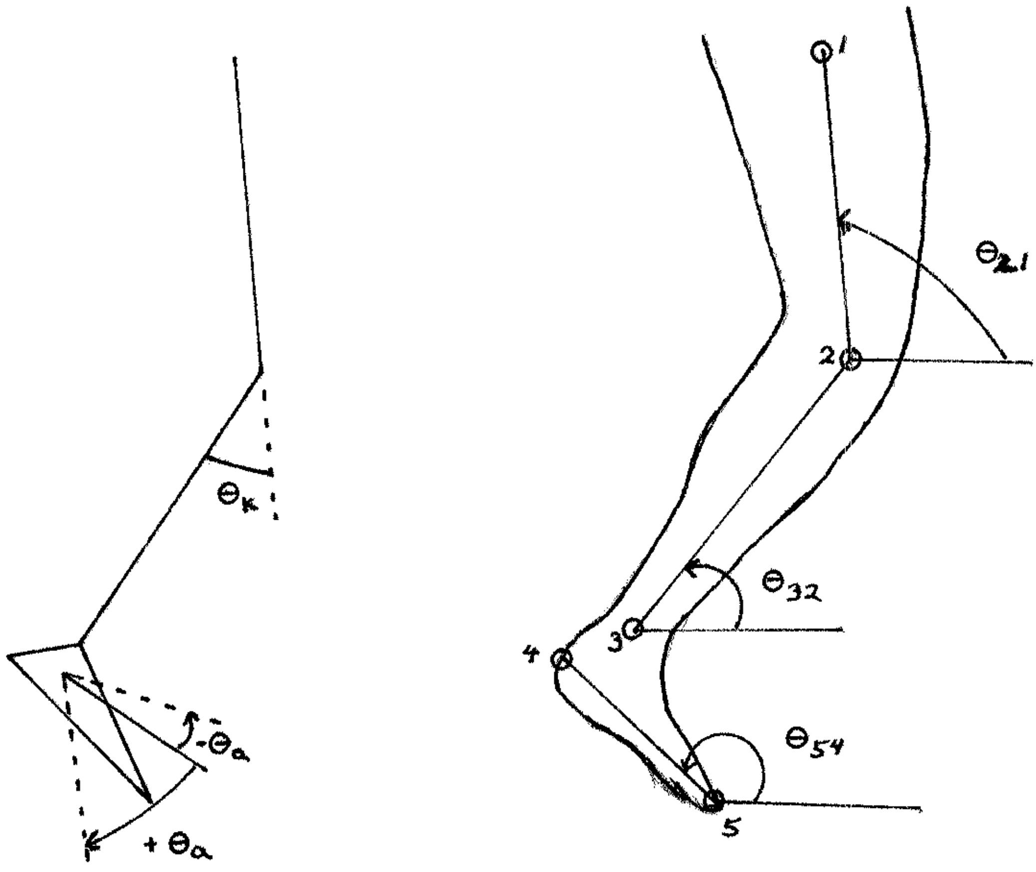

Fig. 6. Joint angle definition

Kinetics

The inverse dynamics approach and Newton's third law were used to solve for the forces that created the motion described in the previous section. The inverse dynamics approach uses the segment's mass and acceleration to solve for the forces acting upon the segment. Newton's third law uses the values obtained in a distal segment to aid in calculating the values in the next proximal segment. The calculation process was begun for the segment on which a measured external force acted, in this case, the foot. For the foot, the forces acting at the ankle are solved from force equations which ultimately solve for the moment about the ankle. These values are then used to solve for the variables of the next proximal segment, the lower leg. In accordance with Newton's third law, "for every action, there is an equal but opposite reaction", the forces and moment are of equal magnitude but opposite in direction.

Force Plate

The ground reaction force is measured directly from the force plate as a function of time. The impact upon the force plate changes the electrical characteristics of the pizoelectric crystals under the 4 corners of the force plate. The amplifier and A/D converter change the electrical signal to a signal proportional to the applied force.

The point of application (center of pressure) of the force, needed to determine distance, e, from the vertical ground reaction force to the center of mass of the foot, was calculated directly from the force plate (See Figure 7). The relative vertical forces seen at the corner transducers were used to determine the center of pressure. The (x,y) coordinates were found from (Winter, 1979):

$$x = \frac{X}{2}\left[1 + \left[\frac{(F_4 + F_3) - (F_1 + F_2)}{F_z}\right]\right] \tag{7}$$

$$y = \frac{Y}{2}\left[1 + \left[\frac{(F_2 + F_3) - (F_1 + F_4)}{F_z}\right]\right] \tag{8}$$

where F_1, F_2, F_3, and F_4 are the vertical forces at the 4 corners and F_z is the sum of the 4 forces.

Using the force plate reference markers, the center of pressure data from the force plate were converted to digitized coordinates. The length and width of the force plate is a known length. The center of pressure coordinates from the force plate can be placed in terms of the scaled digitized coordinates as a ratio of the force plate's width and length. These converted coordinates were used to find the perpendicular distance, e, of the point of application of the vertical ground reaction force to the foot's center of mass.

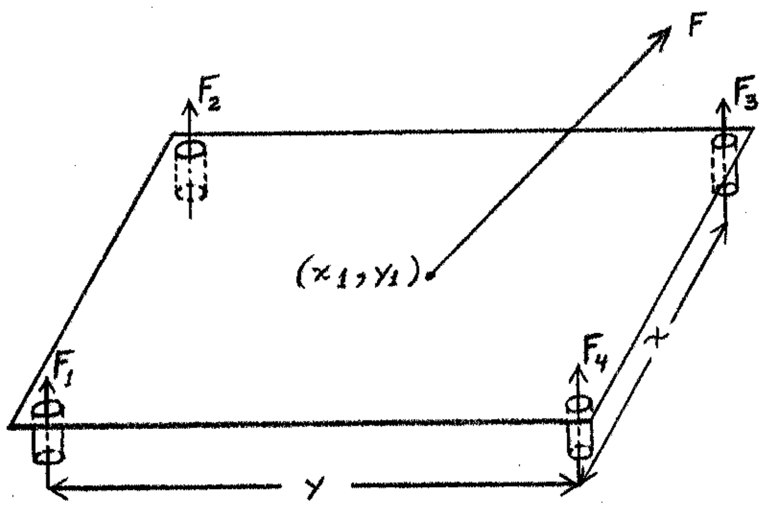

Fig. 7. Center of pressure determination

Net Joint Moments

Newton's laws governing motion were used to calculate the moments about the ankle and knee. The linear analog of the second law

$$\vec{F} = m\vec{a}$$

was used to calculate the forces acting upon the lower extremity segments where $\vec{F}$ represents the resultant vector force acting upon the extremity, m is the mass of the segment, and $\vec{a}$ is the vector acceleration of the segment center of mass. For calculation, the components of the resultant force are identified.

A diagram that details the component forces and moments acting upon a system comprised of one or more segments is called a free body diagram (FBD). For example, Figure 8a is a FBD showing the forces acting upon the foot segment. Figure 8b shows the x and y components acting upon the segment. Since this was a two-dimensional study, a z component was not available. R_x and R_y represent the ground reaction forces where the distal foot contacted the force plate. R_{Ax} and R_{Ay} were the forces at the proximal aspect of the foot. The force of gravity as it acts upon the segment at its center of mass was $m_f g$, where g was the acceleration of gravity (9.8 m/s^2). Therefore, the equations needed to examine the forces at the foot were

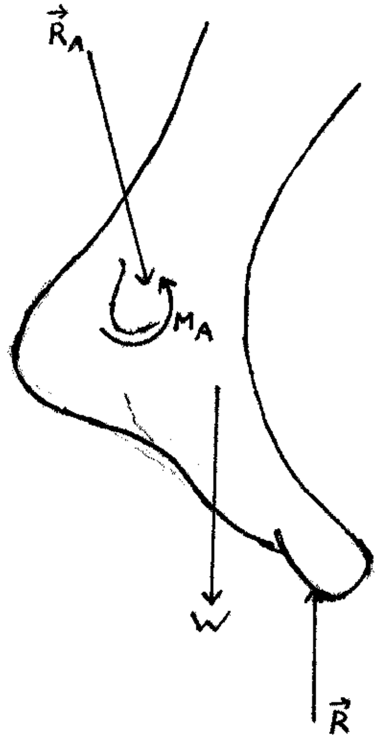

Fig. 8a. Forces and moments acting upon the foot

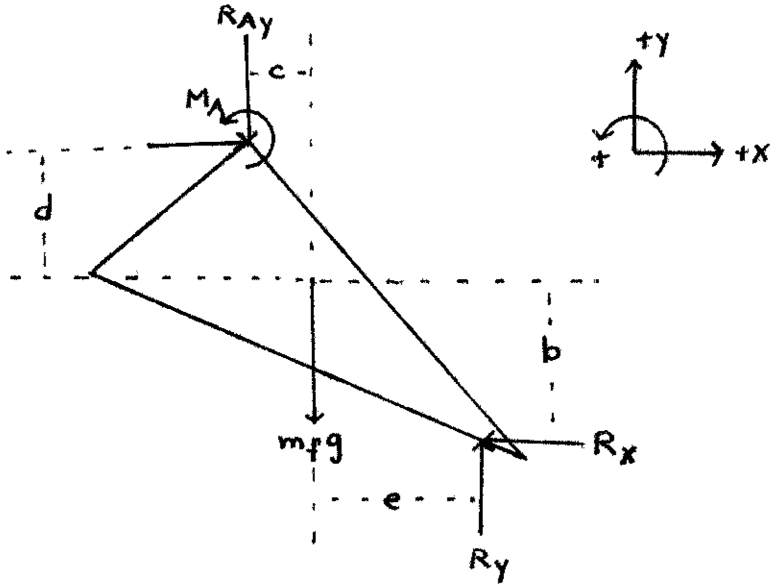

Fig. 8b. Component force and perpendicular distances from CM

$$\Sigma F_x = m_f a_{fx}$$

$$R_{Ax} - R_x = m_f a_{fx}$$

The sum of the forces in the x-direction is equal to the mass of the foot times the acceleration in the x-direction. Referring to Figure 8b, the sum of the forces in the x-direction was R_{Ax} acting in a positive direction and R_x acting in a negative direction. Rearranging to find the unknown, R_{Ax}, the equation becomes

$$R_{Ax} = R_x + m_f a_{fx} \tag{9}$$

Similarly, the sum of the forces in the y-direction was R_y, $m_f g$, and R_{Ay}. Again, solving for the unknown, R_{Ay}, the progression of the equations is

$$\Sigma F_y = m_f a_{fy}$$

$$R_y - m_f g - R_{Ay} = m_f a_{fy}$$

$$R_{Ay} = R_y - m_f g - m_f a_{fy} \tag{10}$$

The angular complement of Newton's second law is represented by

$$\Sigma M = \dot{H}$$

where ΣM represents the resultant vector moment acting at the joint and $\dot{H}$ is the time rate of change of the angular momentum of the segment about its center of mass. If the moment of inertia (I) of the segment acting about the segment center of mass is assumed constant, then

$$\Sigma M = I\alpha \tag{11}$$

is also applicable where α is the angular acceleration of the segment.

The resultant moment may also be characterized by the sum of the forces acting upon the segment multiplied by their perpendicular distance from the center of mass of the segment. Figure 8a shows the forces and moments acting upon the foot segment. Figure 8b shows the component forces acting upon the segment and the perpendicular distance from the center of mass, Therefore, expanding the left side of equation 11, the sums of the moments acting upon the foot segment becomes

$$\Sigma M_A = I_f \alpha_f$$

$$R_y e - R_x b - R_{Ay} c + R_{Ax} d + M_A = I_f \alpha_f$$

Rearranging to find the unknown, M_A, the equation now becomes

$$M_A = R_x b + R_{Ay} c - R_y e - R_{Ax} d - I_f \alpha_f \quad (12)$$

Figure 9 shows FBDs of the foot and lower leg segments. Following the same rationale that was presented above, the following equations were used to calculate the forces and moments acting upon the lower leg.

Lower leg:

$$\Sigma F_x = m_{LL} a_{LLx}$$

$$R_{Kx} - R_{Ax} = m_{LL} a_{LLx}$$

where R_{Kx} and R_{Ax} were the forces acting in the x-direction and m_{LL} was the mass of the lower leg segment and a_{LL} was the acceleration in the x-direction at the center of mass. Solving for the unknown variable, R_{Kx},

$$R_{Kx} = R_{Ax} + m_{LL} a_{LLx} \quad (13)$$

Similarly in the y-direction

$$\Sigma F_y = m_{LL} a_{LLy}$$

$$R_{Ay} - R_{Ky} - m_{LL} g = m_{LL} a_{LLy}$$

with R_{Ky} as the unknown, the equation becomes

$$R_{Ky} = R_{Ay} - m_{LL}g - m_{LL}a_{LLy} \quad (14)$$

$$\Sigma M_K = I_{LL}\alpha_{LL}$$

The sum of the moments acting about the knee are the forces acting on the lower leg multiplied by their perpendicular distances to the segment's center of mass. This is equal to the moment of inertia times the segment's angular acceleration.

$$R_{Ay}h + R_{Kx}n - R_{Ax}i - R_{Ky}j - M_A + M_K = I_{LL}\alpha_{LL}$$

Solving for the unknown, M_K, the equation is now

$$M_K = R_{Ax}i + R_{Ky}j - R_{Ay}h - R_{Kx}n + M_A - I_{LL}\alpha_{LL} \quad (15)$$

The variables used in the equations and with the FBDs are defined in Table 4.

Statistical Analysis

This study was exploratory in nature, designed to form a beginning data base for the mechanics of rope skipping. Comparisons between the 2 conditions were made for the following variables: (a) F_z, (b) moments about the ankle, and (c) moments about the knee. A one factor, repeated measures ANOVA was used to establish any relationship that

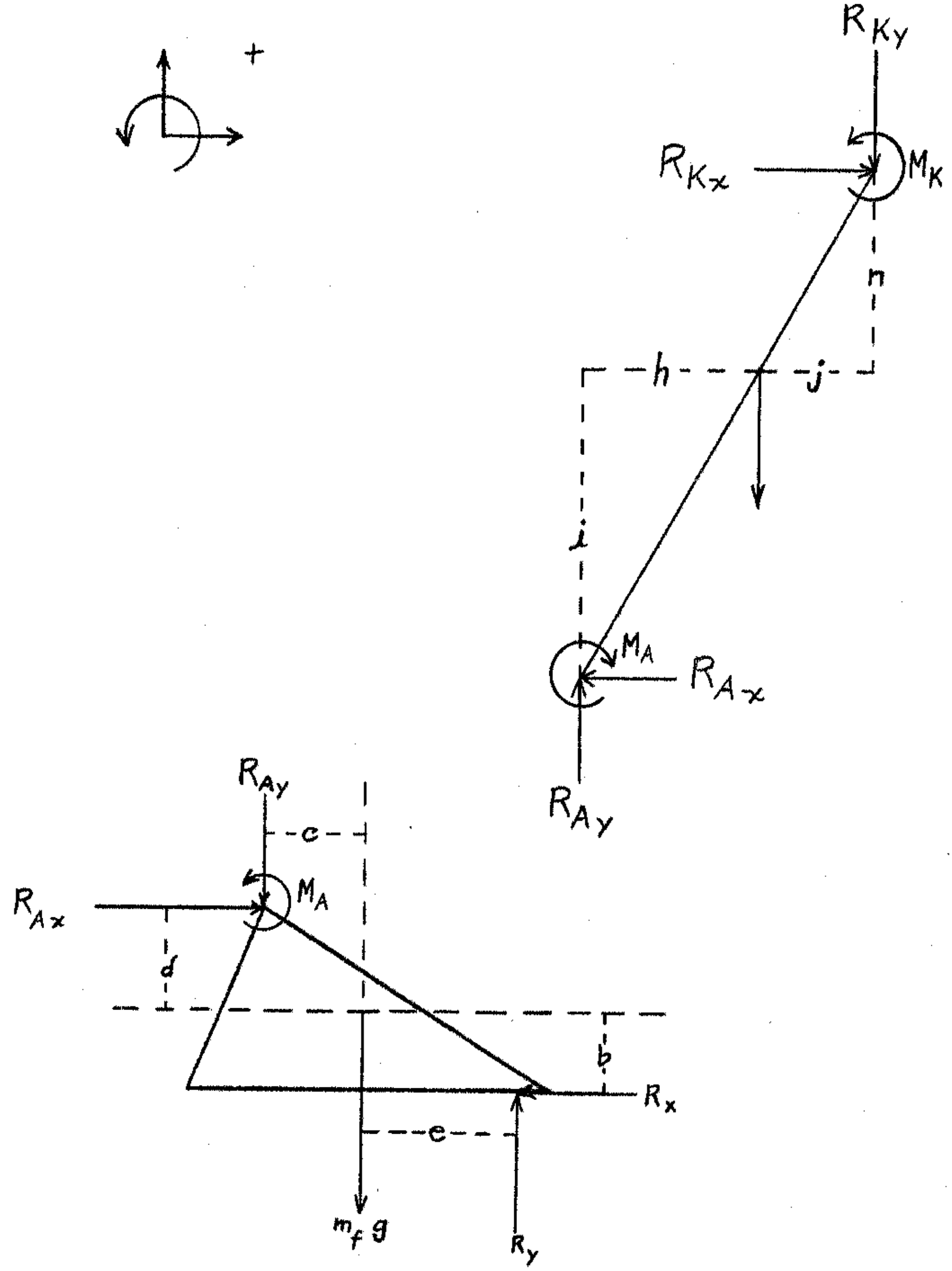

Fig. 9. Free body diagram of foot and lower leg

Table 4

Key to Figure 9

Symbols	Reference
f	foot
LL	lower leg
A	ankle
K	knee
R	a force vector
M	a moment vector
m	segment mass
g	gravitational pull on the segment
x	horizontal coordinate
y	vertical coordinate
b,c,d,e h,i,j,n	perpendicular distances from the line of action of the forces from the center of mass of each segment

might exist between the selected variables over both conditions. No other statistical analysis was performed between or within conditions. The total number of subjects was too small for any other meaningful statistical analysis. However, associations in the data were described and discussed.

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CHAPTER IV

RESULTS

Data were collected for each subject for 2 conditions. Condition 1 was the rhythm bounce style at a nominal rate of 80 turns/min. In Condition 2, the subjects were free to choose the style and rate of skipping for the full 5 minute trial. For each condition, GRF were recorded directly from the force plate, and the moments about the ankle and knee were then calculated from the force plate and film data. Impacts for each condition were selected for further analysis. The means and standard deviations of the GRF and moments for the selected impacts are presented in this chapter. The joint angles and joint motions during the impact phase are also described. A statistical analysis using one way ANOVAs comparing chosen dependent variables between the 2 conditions is also included in this chapter.

Selection of Impacts

For the rhythm bounce style, the subjects jumped over the rope as it passed and then performed another, smaller jump as the rope was overhead. The impact following the jump of the rope was designated as the primary impact. The impact from the second jump as the rope was overhead was designated as the secondary impact. For Condition 1, two consecutive impacts, one primary and one secondary, were chosen as being representative of that trial.

For Condition 2, four subjects chose a single bounce style, 3 chose a jogging style, and the remaining 3 subjects chose the rhythm bounce as their preferred style. The single bounce is similar to the rhythm bounce except that there is only one jump, when the rope passes under the feet, instead of two jumps. The jogging style simulates jogging in place. Instead of both feet jumping together, the weight is alternated between the legs per each turn of the rope. One impact was chosen as representative of that trial for both the single bounce and jogging styles. As with Condition 1, there were two consecutive impacts chosen for the subjects who chose the rhythm bounce style.

There were 2 to 8 impacts within the target area for all subjects in both conditions, except Subject 5. Subject 5 had no usable impacts in Condition 1. Usable impacts were determined by examination of the center of pressure data derived from the force plate. Impacts occurring in the latter phase of collection from the force plate were found to be influenced by a rebound effect off the force plate. Once a subject is airborne, the force plate is designed to reset to zero across all channels. However, when film data were coordinated with force plate readings, it was ascertained that the force plate was not quickly resetting after approximately 2 seconds of collection. Therefore, any impact occurring after 1.7 seconds was judged to be suspect and was not used for analysis. Two to four impacts remained for consideration following this procedure.

The choices were further narrowed by reviewing the force plate data in conjunction with the film data. The impacts that were clearly within the target area and appeared under control by the subject (as seen on the film) were chosen as representative of that particular trial.

Condition 1

All subjects were able to perform the rhythm bounce style with a skipping rate of 70 - 80 turns/min. Subject 5 was able to perform the style, but had no usable impacts for analysis.

Analysis of the primary impacts is presented here. Trends and comparisons within and between conditions are discussed later.

Ground Reaction Force

The vertical (F_z), anterior-posterior (F_y), and medial-lateral (F_x) forces were recorded directly from the force plate and converted from force plate units to Newtons. For comparison, and to negate the effects of the difference in the subjects' body weight, the forces were converted into units of body weight (BW).

The range of peak vertical force was 1.565138 BW for Subject 10 to 3.72956 BW for Subject 4. The mean peak force was 2.076 $\pm$ .622 BW with a mean time-to-peak of .087 $\pm$ .011 s. The peak vertical force for each subject as well as the time-to-peak for each are listed in Table 5.

Table 5

Peak GRF (BW) and Time-to-Peak of F_z (s)

Subject	Peak F_z	Time-to-Peak	Peak F_y	Peak F_x
1	1.95771	.10263	-.84826	-.03597
2	1.75286	.0933	.409611	-.08009
3	1.97795	.10076	-.64388	-.20728
4	3.72956	.06718	.853257	-.89098
6	1.78958	.07651	.249180	-.36721
7	1.95657	.0933	-.19327	-.24973
8	2.34712	.0821	.170115	-.17471
9	1.61014	.08397	-.2729	-.40156
10	1.56514	.0877	.256881	-.31009

All measurements of F_y and F_x were less than one BW with peak F_y ranging from .1702 BW by Subject 8 to .85326 BW for Subject 4. F_x ranged from -.0800915 BW for Subject 2 to -.890981 BW for Subject 4. (See Table 5). Mean F_y was .433 $\pm$ .276 BW while the mean of F_x was .332 $\pm$ .232 BW.

Force-Time Curves

Figures 10a and 10b are the force-time curves of the primary impacts of Subject 2 and Subject 10 respectively. They are generally representative of the force-time curves seen in this condition. There was a rise to one dominant peak in F_z within the first half of the impact phase followed by a gradual decline. There was a greater slope during the rise in F_z than in the decline. F_y and F_x were more variable but with considerably less magnitude.

Moments

Rotation in the counterclockwise direction was considered positive with clockwise represented by negative values. The peak moments at the ankle were all negative except for Subject 4. The range of peak moments about the ankle was -25.49502 N.m by Subject 9 to -148.5181 N.m by Subject 1. The mean peak ankle moment was 73.402 $\pm$ 44.186 N.m with a mean time-to-peak of .092 $\pm$ .012 s. The mean knee moment was 161.764 $\pm$ 84.544 N.m out of a range of -65.3124 N.m from Subject 6 to -334.4394 N.m by Subject 1. The mean time-to-peak was .095 $\pm$ .012 s. The peak ankle and knee moments with their times-to-peak are presented in Table 6.

Moment-Time Curves

Figures 11, 12, and 13 illustrate the graphical depiction of the time histories for the moments of Subjects 2, 3, and 4 respectively. These graphs represent the three types of

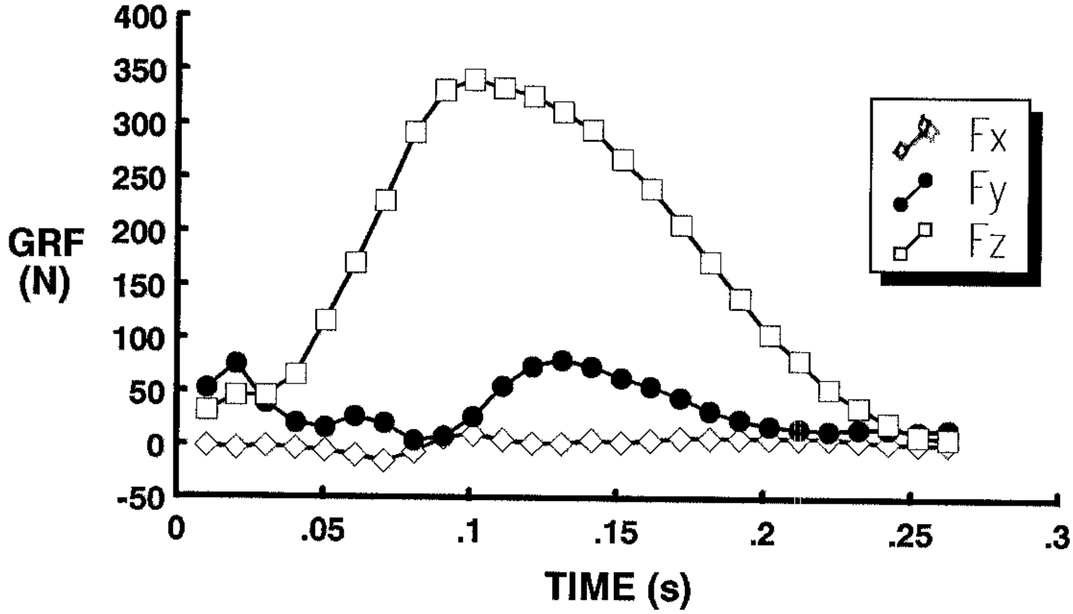

Fig. 10a. Force-time curve for Subject 2, Condition 1

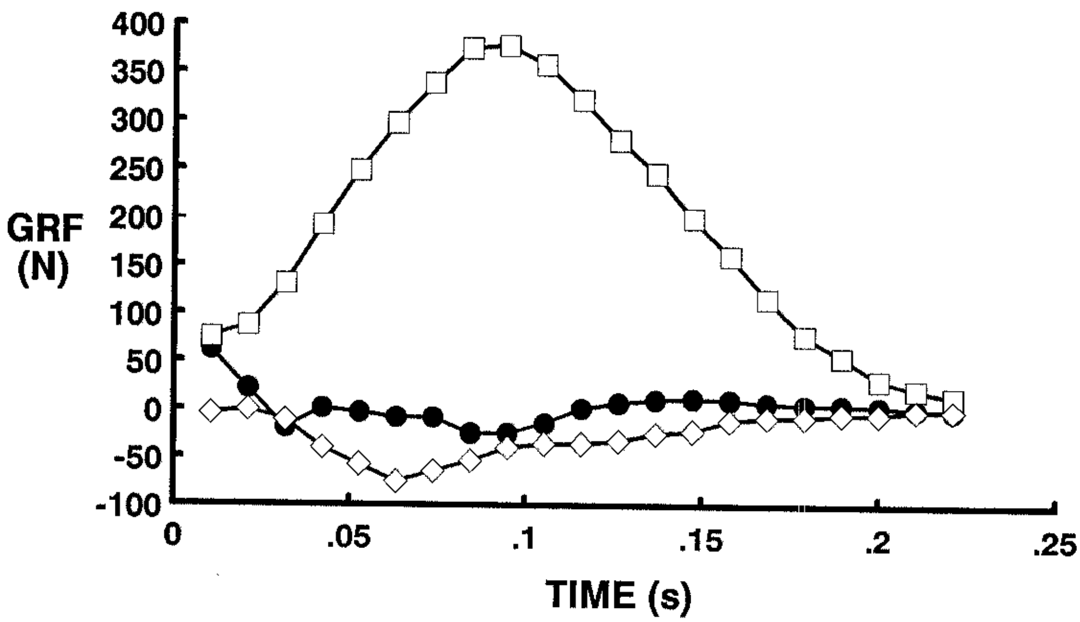

Fig. 10b. Force-time curve for Subject 10, Condition 1

moment-time curves observed in Condition 1. The ankle moments and knee moments in Figure 11 generally follow the same pattern which closely approximate each other in magnitude. In Figure 12, the ankle moments follow the same pattern as the knee, but the knee magnitudes are greater than the ankle. There was little resemblance between the ankle and knee in magnitude and direction in Figure 13.

Table 6

Peak Moments (N.m) and Time-to-Peak (s) for Ankle and Knee

Subject	Ankle Moment	Time-Peak	Knee Moment	Time-Peak
1	-148.5181	.10101	-334.4394	.10101
2	-112.8464	.09091	-151.0841	.09091
3	-75.7556	.11458	-234.9186	.11458
4	69.76498	.09375	195.1629	.10417
6	-26.23655	.07368	-65.3124	.07368
7	-49.73546	.09474	-95.75587	.09474
8	-116.7988	.08421	-173.1165	.09474
9	-25.49502	.08421	-110.0517	.08421
10	-35.47069	.09474	-96.038	.09474

Joint Angles

Ankle and knee motions were generally smooth and synchronous upon impact. As the ankle dorsiflexed, the knee

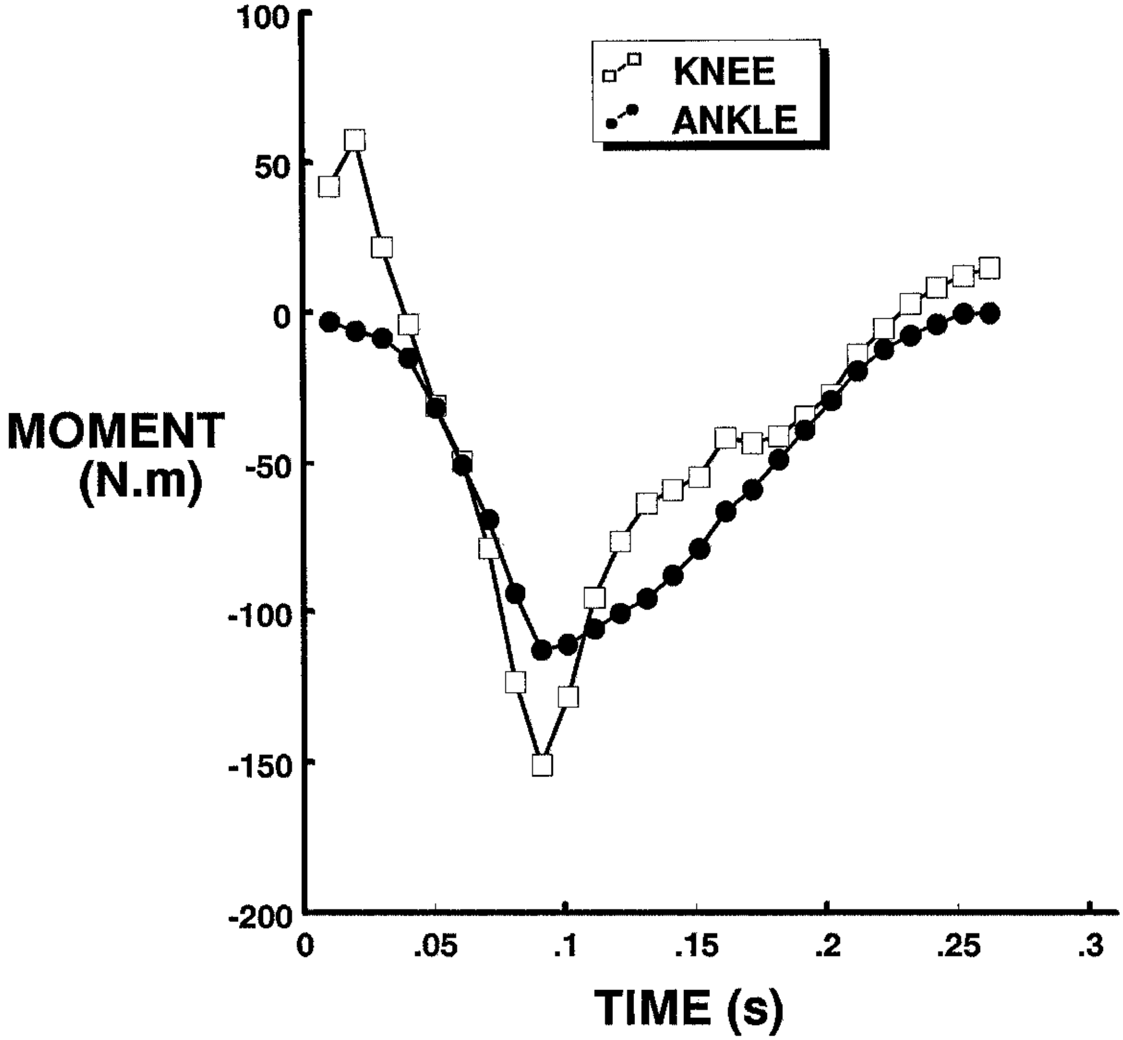

Fig. 11. Moment-time curve for Subject 2, Condition 1

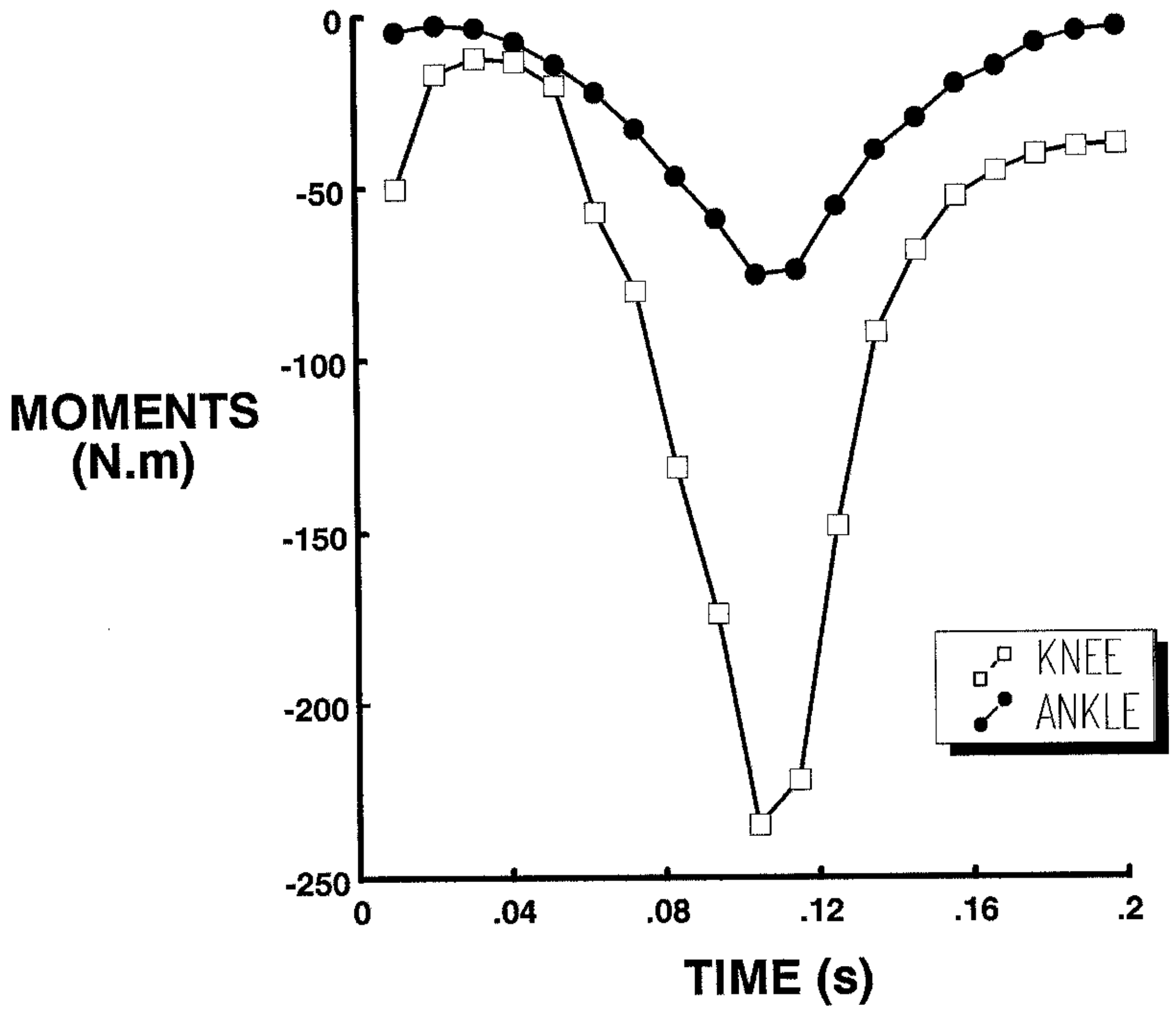

Fig. 12. Moment-time curve for Subject 3, Condition 1

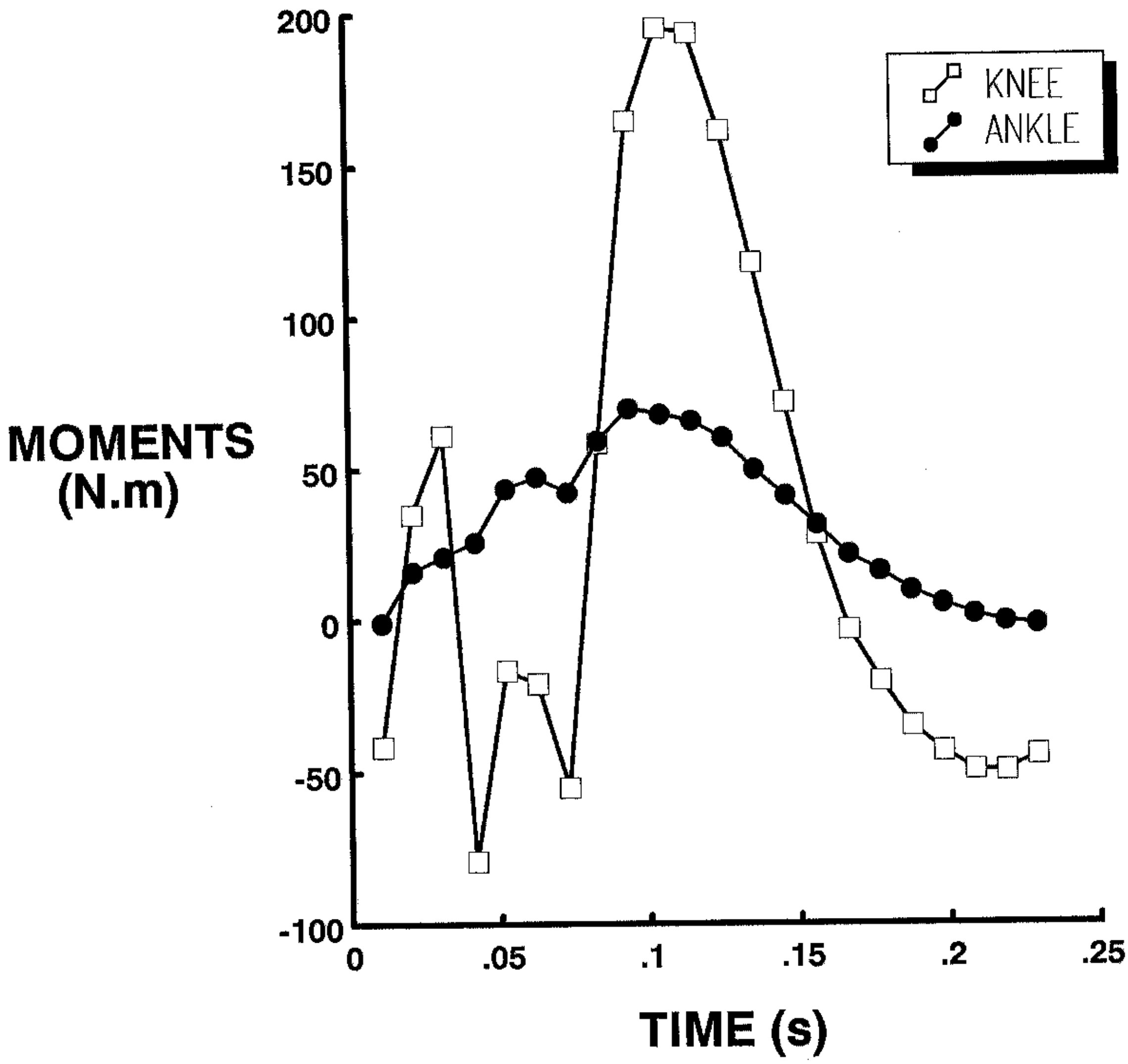

Fig. 13. Moment-time curve for Subject 4, Condition 1

flexed until approximately midway through the impact when the direction reversed: the ankle began to plantarflex as the knee extended. In all subjects, except Subjects 3 and 9, peak dorsiflexion occurred either at the same time or just preceding peak knee flexion.

The amount of motion of both joints varied from subject to subject. Figures 14a and 14b show the ankle and knee motions of Subjects 3 and 8. Although the ankle was moving nearly through its full range of dorsiflexion, there was little knee motion by Subject 3. Subject 8 demonstrated a pattern of knee flexion occurring as the ankle dorsiflexed. Although the knee was using only a portion of its range of motion, it was acting in concert with the ankle following the same timing sequence.

Condition 2

In Condition 2, the subjects were free to choose the style and skipping rate for the 5 minute session. Subjects 1, 3, 7, and 8 chose the single bounce. Subjects 5, 9, and 10 chose the jogging style. Subjects 2, 4, and 6 chose the rhythm bounce style. Table 7 summarizes the style and skipping rate chosen by each subject. The data for Condition 2 are presented separately for each style.

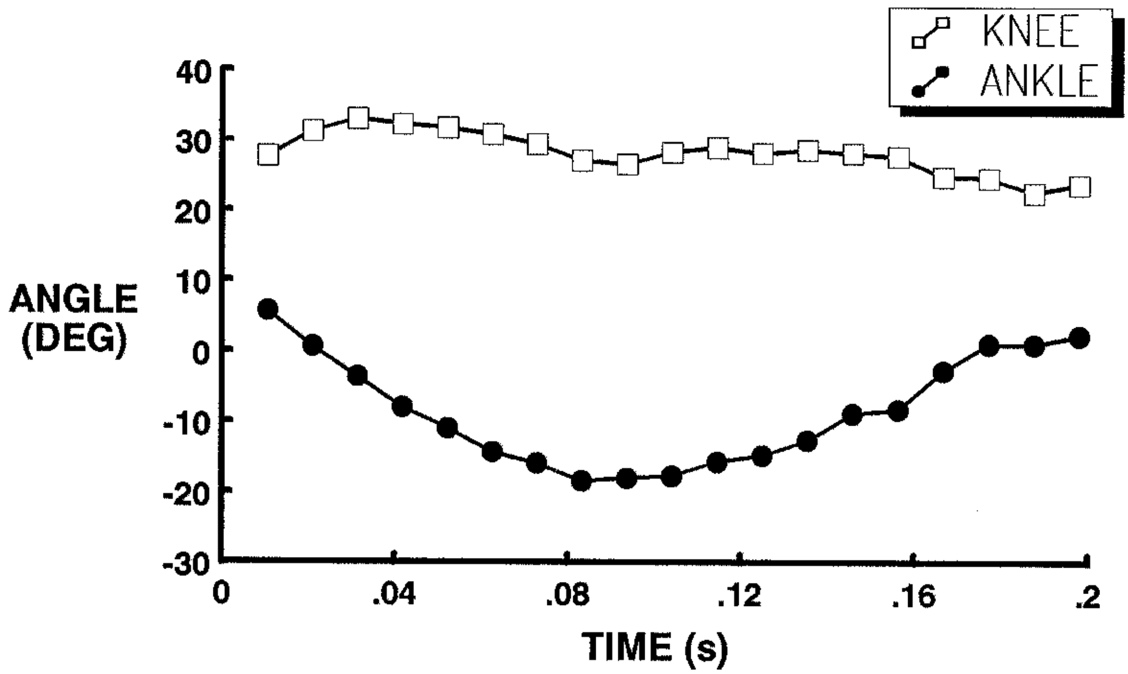

Fig. 14a. Joint motions for Subject 3, Condition 1

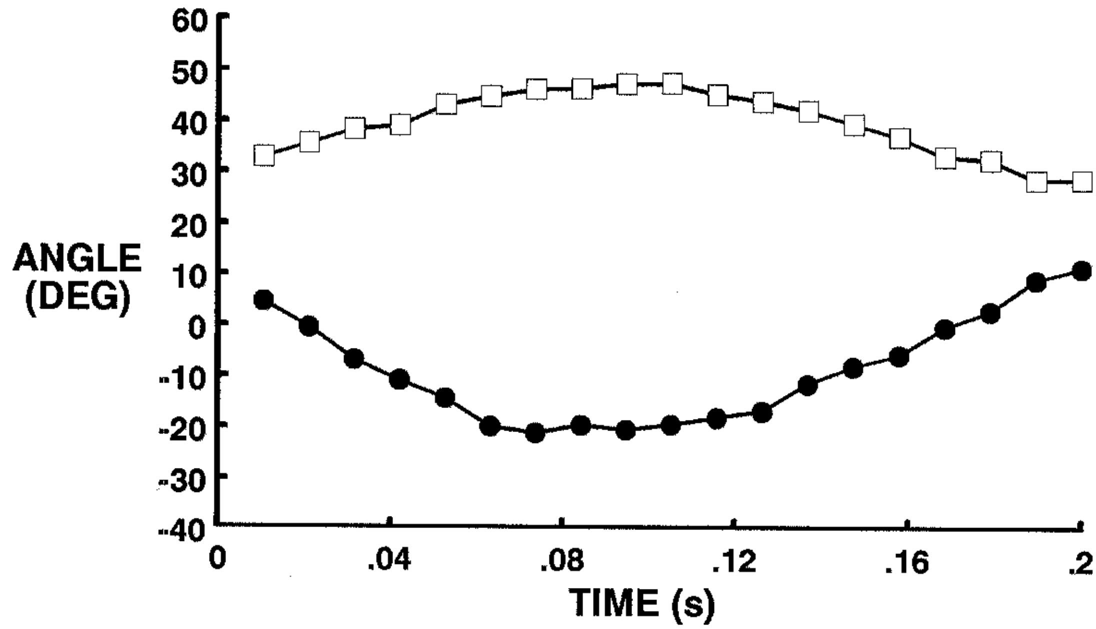

Fig. 14b. Joint motions for Subject 8, Condition 1

Table 7

Style and Skipping for Condition 2

Subject	Style	Rate/Min
1	Single Bounce	74
2	Rhythm Bounce	77
3	Single Bounce	120
4	Rhythm Bounce	74
5	Jogging	124
6	Rhythm Bounce	72
7	Single Bounce	141
8	Single Bounce	127
9	Jogging	115
10	Jogging	133

Ground Reaction Force

Single Bounce

The vertical peak forces ranged from 1.942668 BW for Subject 3 to 3.004598 BW for Subject 8 with a mean and standard deviation of 2.429 $\pm$ .44 BW. Time-to-peak mean was .11 $\pm$ .028 s. As with Condition 1, peak F_x and F_y were less than 1 BW for all subjects. The lowest F_x was -.3409334 BW for Subject 7, while the highest peak recorded was -.4551719 BW by Subject 8. The mean for F_x was .386 $\pm$ .052 BW. The

F_y ranged from .2128121 BW by Subject 7 to -.4925368 BW by Subject 1. The mean for F_y was .327 $\pm$ .138 BW. The peak GRF with the time-to-peak for F_z for this style are presented in Table 8.

Table 8

Peak GRF (BW) and Time-to-Peak (s) - Single Bounce

Subject	Peak F_z	Time	Peak F_y	Peak F_x
1	2.31343	.09889	-.49254	-.398010
3	1.94267	.12316	-.390297	-.350606
7	2.45385	.09703	.2128121	-.340933
8	3.00460	.07651	-.213793	-.455172

The force-time curves of the GRF for the single bounce style were similar to the force-time curves observed in Condition 1. F_z was the dominant curve with a gradual rise to peak followed by a gradual decline. F_x and F_y were less in magnitude than F_z. Variability was observed in magnitude and direction both within and between F_x and F_y for the subjects. Figure 15 shows the force-time curve for Subject 8.

Jogging Style

The lowest peak F_z was 2.00734 BW recorded by Subject 10 while Subject 5 recorded the highest peak F_z of

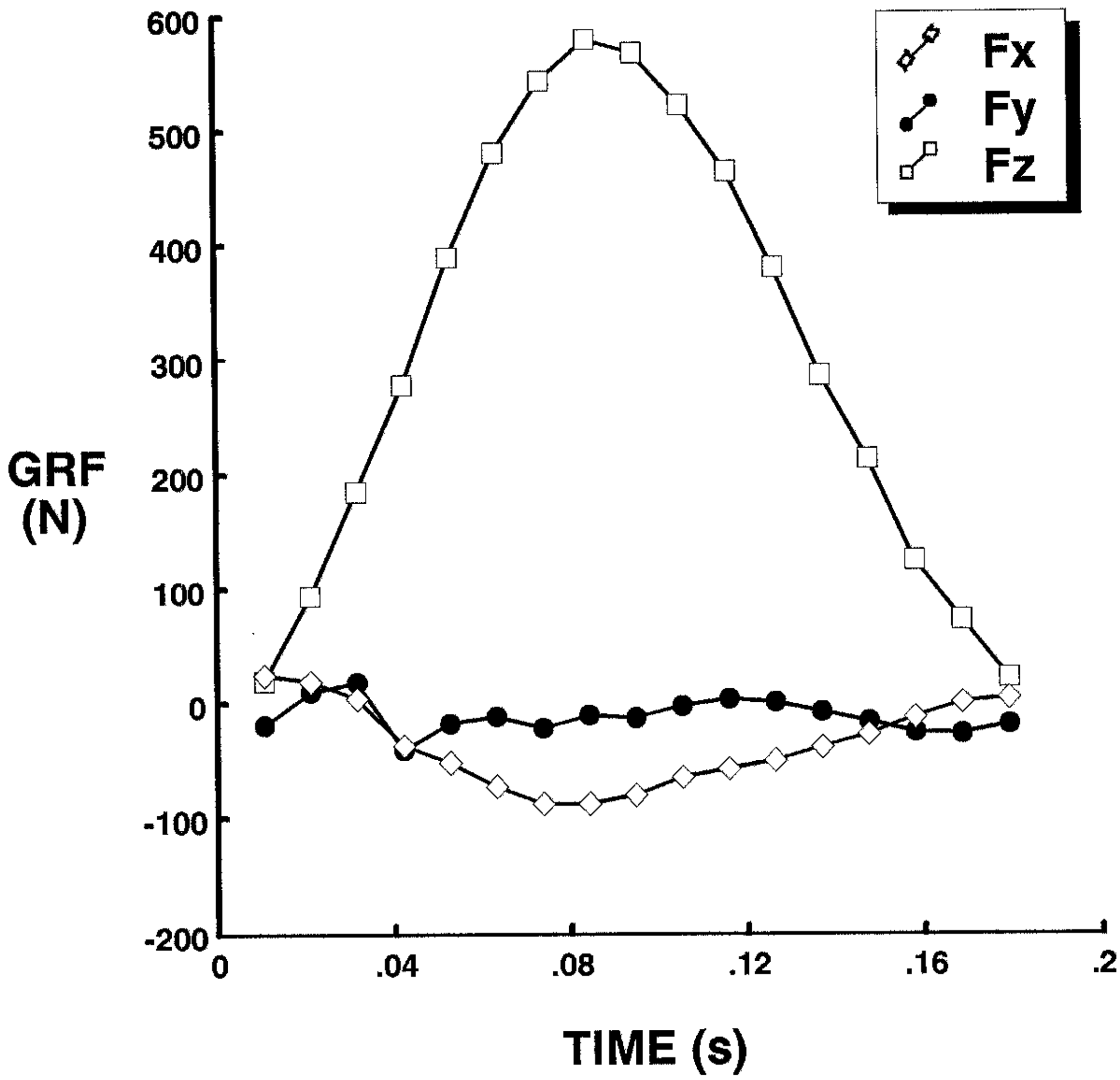

Fig. 15. Force-time curve for Subject 8, Condition 2

2.698718 BW. The mean peak F_z was 2.251 $\pm$ .388 BW with the mean time-to-peak of .142 $\pm$ .047 s. The lowest F_x recorded was -.155945 BW by Subject 9 while the highest was -.6570507 BW by Subject 5. F_y ranged from .1130604 BW by Subject 9 to .9887882 BW by Subject 5. Means for each component were .482 $\pm$ .283 BW for F_x and .444 $\pm$ .476 BW for F_y. Table 9 contains the peak values for this style.

Table 9

Peak GRF (BW) and Time-to-Peak (s) - Jogging

Subject	Peak F_z	Time	Peak F_y	Peak F_x
5	2.69872	.13995	.988782	-.657051
9	2.04678	.19033	.113060	-.155945
10	2.00734	.09703	.229358	-.633024

The force-time curves seen for this style vary from all other curves in two ways:

1. the duration of the peak and near-peak vertical forces were longer in this style, and
2. there were greater differences in magnitude between F_x and F_y except for Subject 9.

Figures 16a and 16b show these differences for Subjects 9 and 10 respectively.

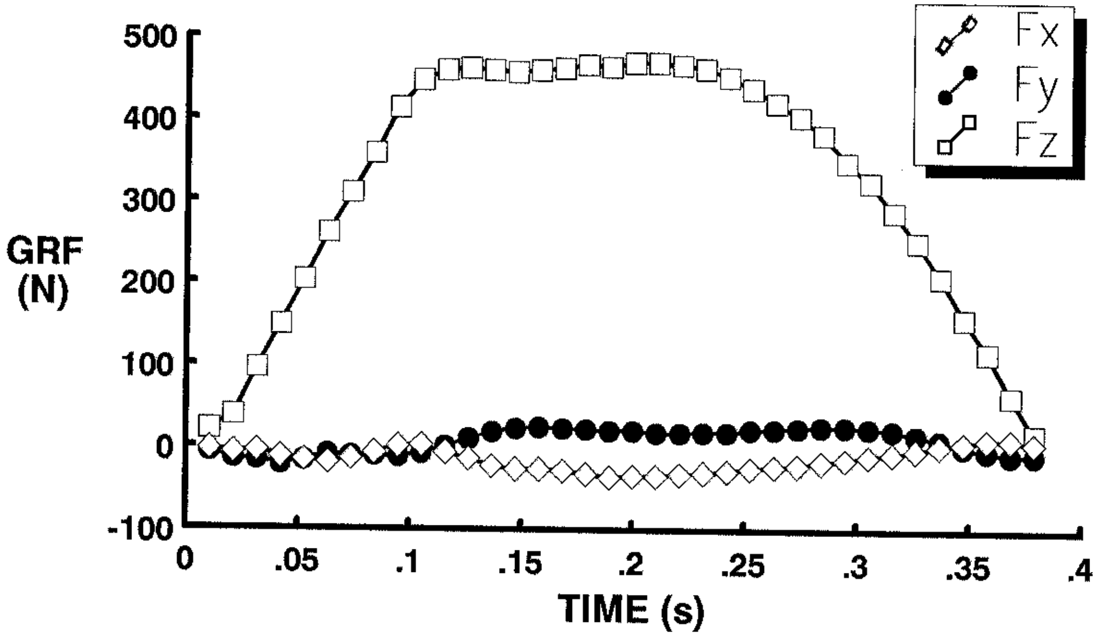

Fig. 16a. Force-time curve for Subject 9, Condition 2

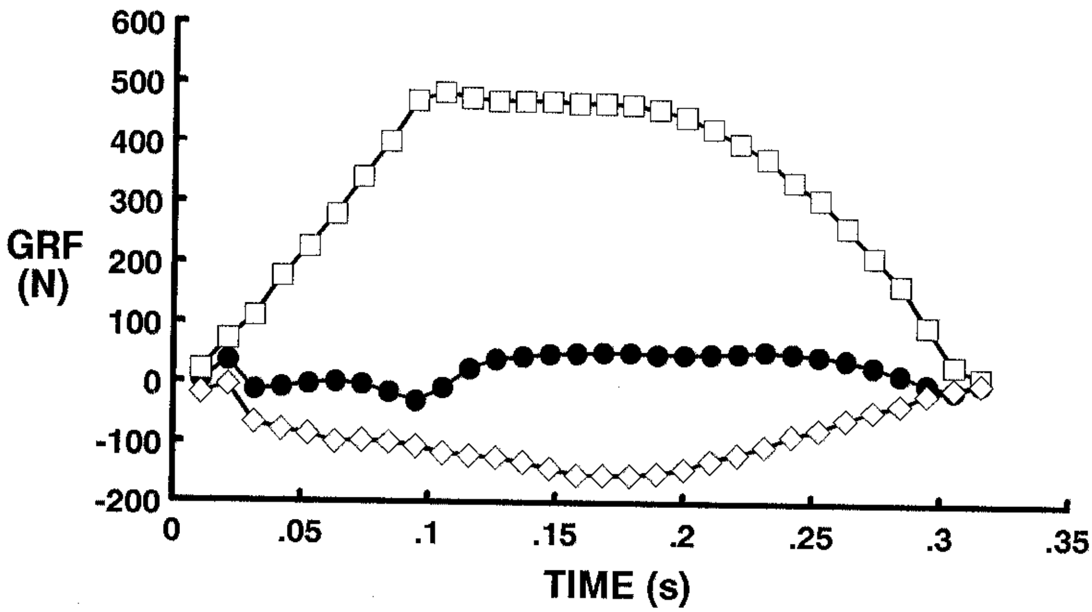

Fig. 16b. Force-time curve for Subject 10, Condition 2

Rhythm Bounce

Subject 6 had the lowest peak F_z of the 3 subjects in this style with 1.22623 BW. Subject 4 had the highest F_z with 3.004193 BW. The mean of this group was 2.003 $\pm$ .91 BW. The mean time-to-peak was .081 $\pm$ .006 s. The range for F_x was -.1578944 BW by Subject 2 to -.7213107 BW by Subject 6 with its mean of .505 $\pm$ .304 BW. Although Subject 6 had the lowest peak F_z for this style, he had the highest F_y of 1.938798 BW, the highest F_y recorded for any subject, any condition, and the only F_y over 1 BW. The lowest F_y for this style was .5469106 BW recorded by Subject 2. The mean F_y was 1.082 $\pm$ .749 BW. Table 10 presents the peak values for this style.

Table 10

Peak GRF (BW) and Time-to-Peak (s) - Rhythm Bounce

Subject	Peak F_z	Time	Peak F_y	Peak F_x
2	1.78	.08584	.409611	-.080092
4	3.00419	.07464	-.76100	-.635218
6	1.22623	.08397	1.93879	-.721311

All 3 force-time curves for this style were different. Figures 17, 18, and 19 show the curves for Subjects 2, 4, and 6. Subjects 2 and 4 demonstrated the general pattern as was

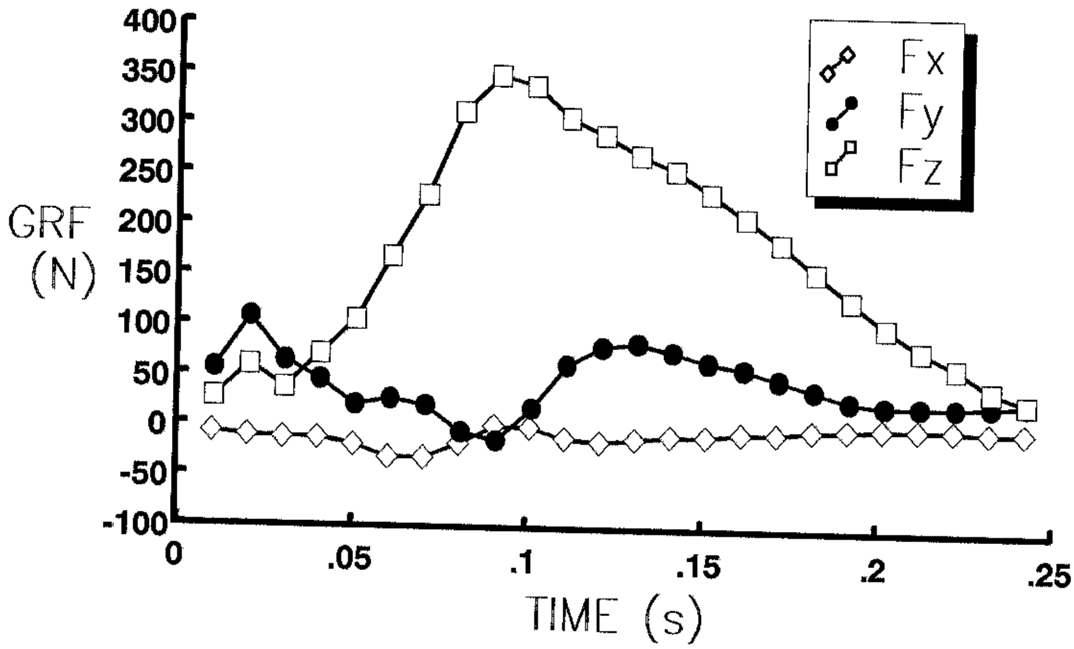

Fig. 17. Force-time curve for Subject 2, Condition 2

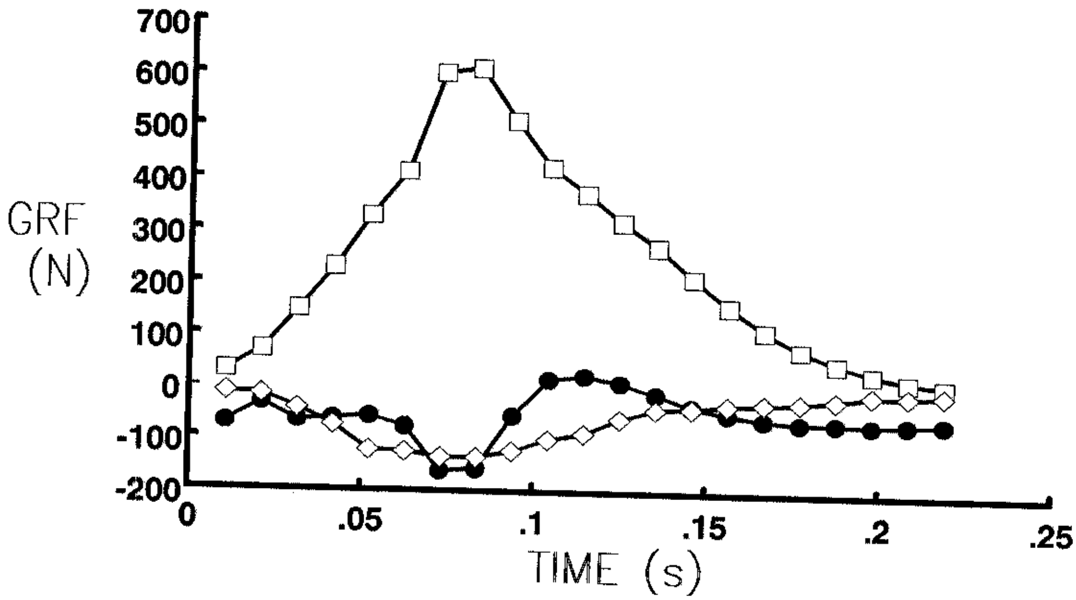

Fig. 18. Force-time curve for Subject 4, Condition 2

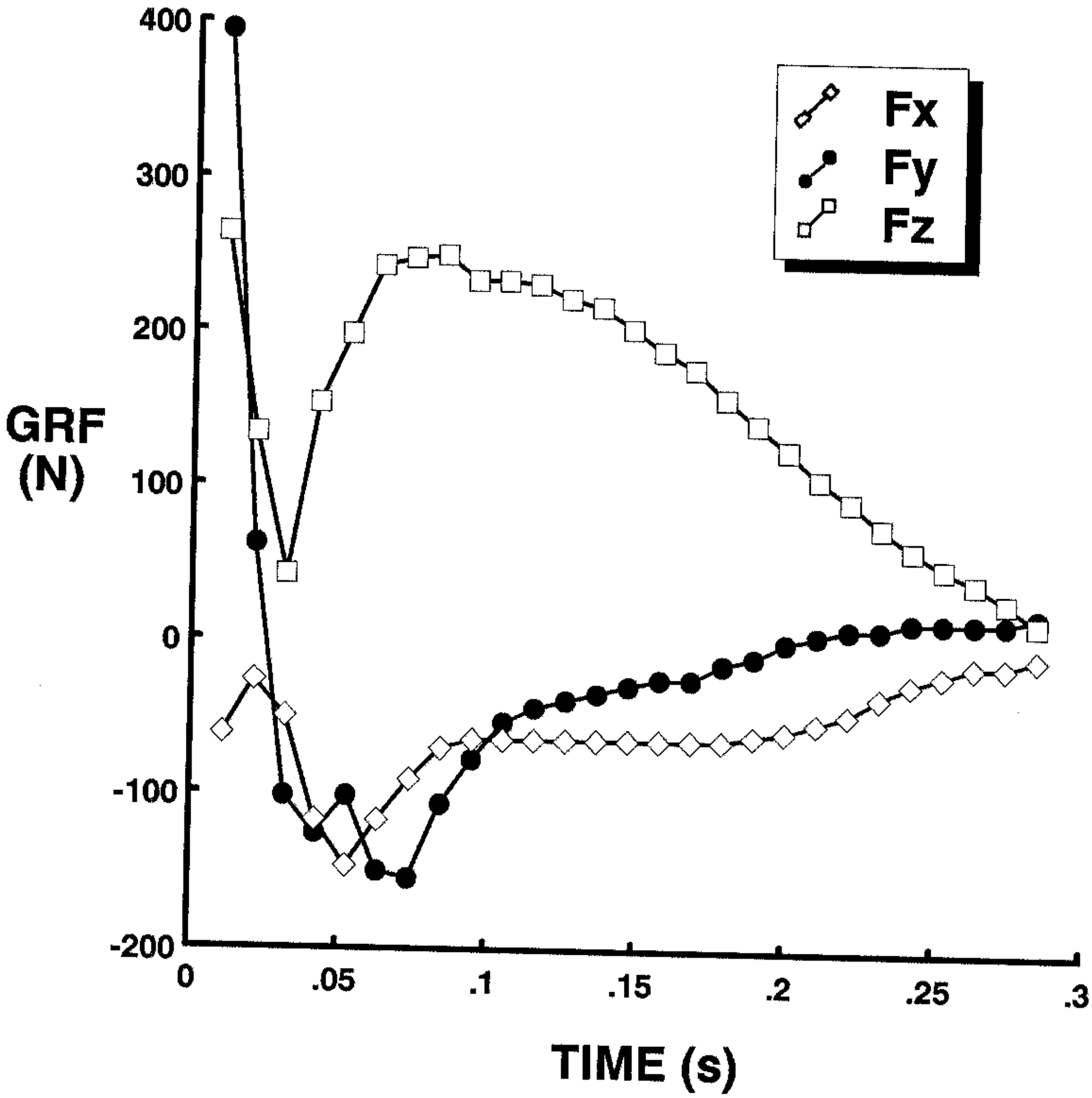

Fig. 19. Force-time curve for Subject 6, Condition 2

demonstrated in Condition 1 with F_z going to peak in the first half of the impact phase followed by a gradual, slower decline. The duration of peak and near-peak values was shorter for Subject 4. Variability in F_x and F_y was present in all three. Subject 6 showed a large initial peak followed by a quick decline and subsequent building to a second peak for F_z. The initial F_z peak was accompanied by a larger initial F_y peak that quickly declined.

Moments

Single Bounce

Subject 3 had the lowest peak moment about the ankle of 8.6686 N.m. The upper limit of the range was -117.0642 N.m by Subject 8. The mean ankle moment for this group was 75.846 $\pm$ 49.119 N.m at the mean time-to-peak of .102 $\pm$ .012 s.

The range for the moments about the knee was 46.94302 N.m by Subject 7 to -245.4554 N.m by Subject 1. The mean for the knee was 148.939 $\pm$ 89.701 N.m. The mean time-to-peak was .075 $\pm$ .039 s. The peak values for this style are presented in Table 11.

The same three associations in the moment-time curves observed in Condition 1 were also present in the moment-time curves for this style. Figures 20a and 20b show the curves for Subjects 8 and 3. The ankle and knee moments follow the same pattern for Subject 8 but there was variability in magnitude and direction for Subject 3.

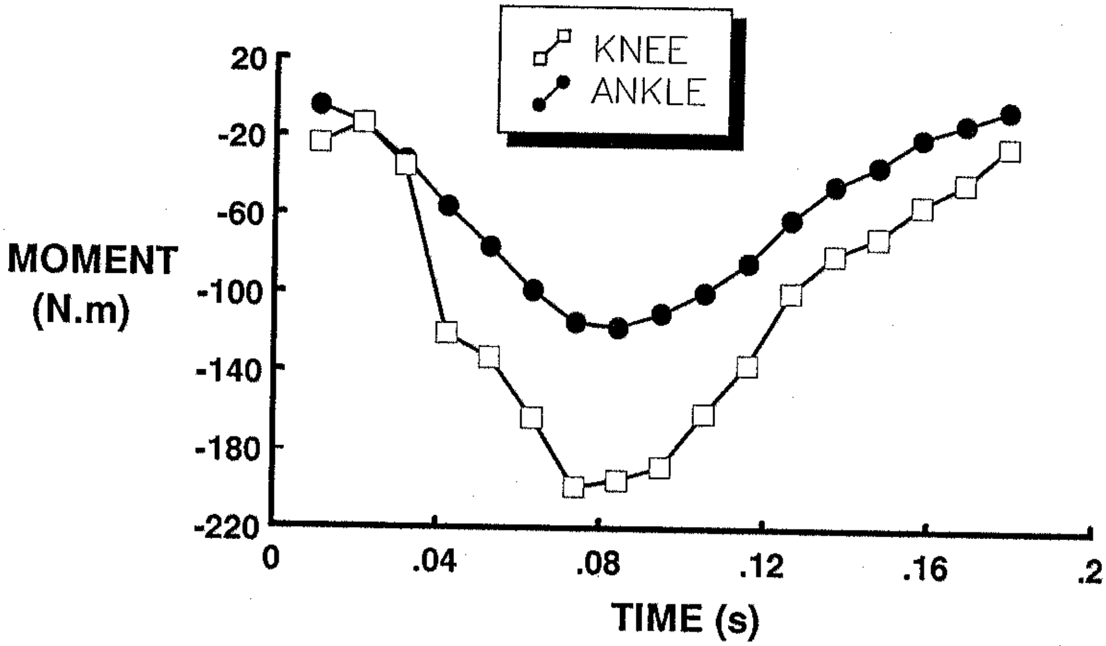

Fig. 20a. Moment-time curve for Subject 8, Condition 2

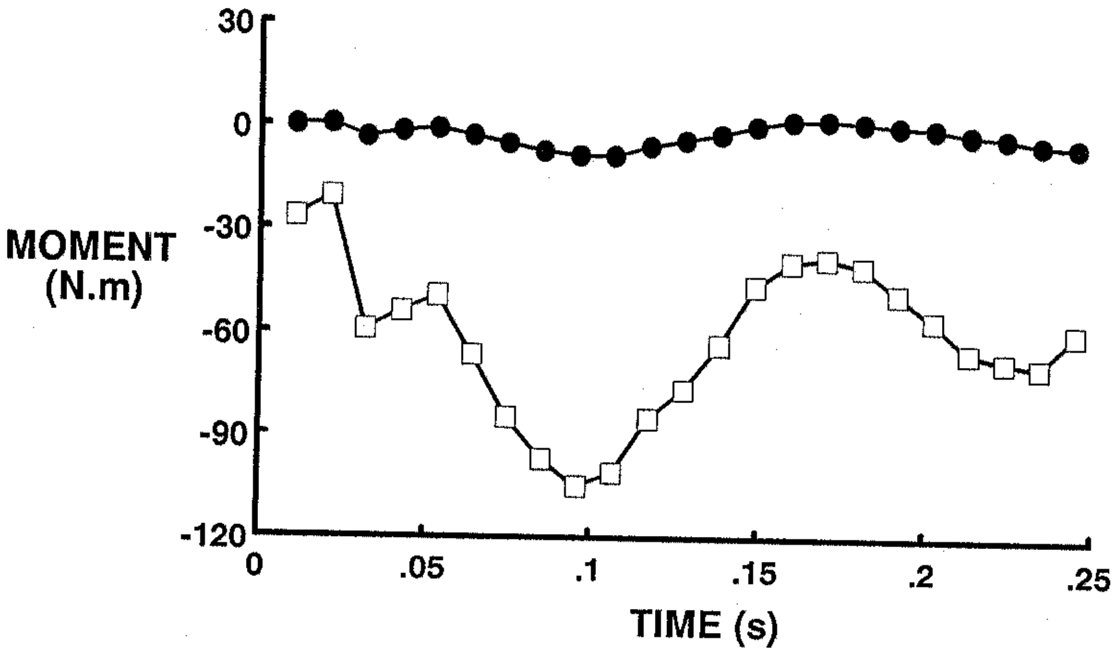

Fig 20b. Moment-time curve for Subject 3, Condition 2

Table 11

Peak Moments (N.m) and Times-to-Peak (s)

Subject	Ankle Moments	Time	Knee Moments	Time
1	-107.3898	.11111	-245.4554	.11111
3	-8.668555	.01638	-104.7449	.09574
7	70.26085	.10526	46.94302	.02105
8	-117.0609	.08421	-198.6109	.07368

Jogging

Subject 5 had the lowest peak moments for both the ankle and the knee, -12.07495 N.m for the ankle and 85.17697 N.m for the knee. Subject 10 had the highest peak moments for both joints, -98.43842 N.m about the ankle and -154.6563 N.m about the knee. The mean ankle moment was 67.659 ± 48.23 N.m at a mean time-to-peak of .109 ± .006 s. The mean knee moment was 121.048 ± 34.795 N.m at .12 ± .035 s. Table 12 contains the peak values for this style.

The ankle and knee moments were closely approximated on the moment-time curves for Subjects 9 and 10. The magnitudes demonstrated a rise in the negative direction, reached a plateau, then began a positive ascent. However, there was little change in ankle magnitude with variable knee moments in magnitude and direction across time for Subject 5.

Table 12

Peak Moments (N.m) and Times-to-Peak (s) - Jogging

Subjects	Ankle Moments	Time	Knee Moments	Time
5	-12.07495	.10638	85.17697	.15957
9	-92.46272	.11579	-123.3121	.10526
10	-98.43842	.10526	-154.6563	.09474

Rhythm Bounce

The highest peak moments recorded in this condition for this style were -180.667 N.m at the ankle and -385.4587 N.m at the knee, both by Subject 4. The lowest peak moment at the ankle was -47.4267 N.m by Subject 6 while the lowest at the knee was -148.001 N.m by Subject 2. (See Table 13 for values.) The mean for the ankle moments was 107.918 $\pm$ 67.46 N.m at a time-to-peak of .083 $\pm$ .009 s. The mean knee moment was 273.308 $\pm$ 119.273 N.m at .058 $\pm$ .042 s.

The three types of moment-time curves observed throughout both conditions were again actualized in this style, each subject following one type. The ankle and knee moments for Subject 2 generally followed the same pattern, approximating each other. Subject 4 demonstrated a similar pattern for the ankle and knee but with the magnitudes of the knee greater than the ankle. Variability in magnitude and direction of the moments was demonstrated by Subject 6.

Table 13

Peak Moments (N.m) and Times-to-Peak (s) - Rhythm Bounce

Subject	Ankle Moments	Time	Knee Moments	Time
2	-95.66125	.09091	-148.001	.09091
4	-180.6667	.08333	-385.4587	.07292
6	-47.4267	.07368	286.4658	.01053

Angles

As Figures 21 - 23 (representing Subjects 3, 4, and 9) demonstrate, the ankle knee angles followed the same sequencing across all subjects and groups in Condition 2 as in Condition 1. All subjects demonstrated good range of motion at the ankle with varied motion at the knee. Subject 9 employed a larger amount of knee flexion during impact than Subject 3. Peak dorsiflexion occurred at the same time or just prior to peak knee flexion in all subjects except Subjects 2 and 10.

Statistical Analysis

The means and standard deviations for all the dependent variables for both conditions are listed in Table 14.

The variables of interest for comparison between the conditions were F_z, moments about the ankle, and moments about the knee. A one factor, repeated measures ANOVA was

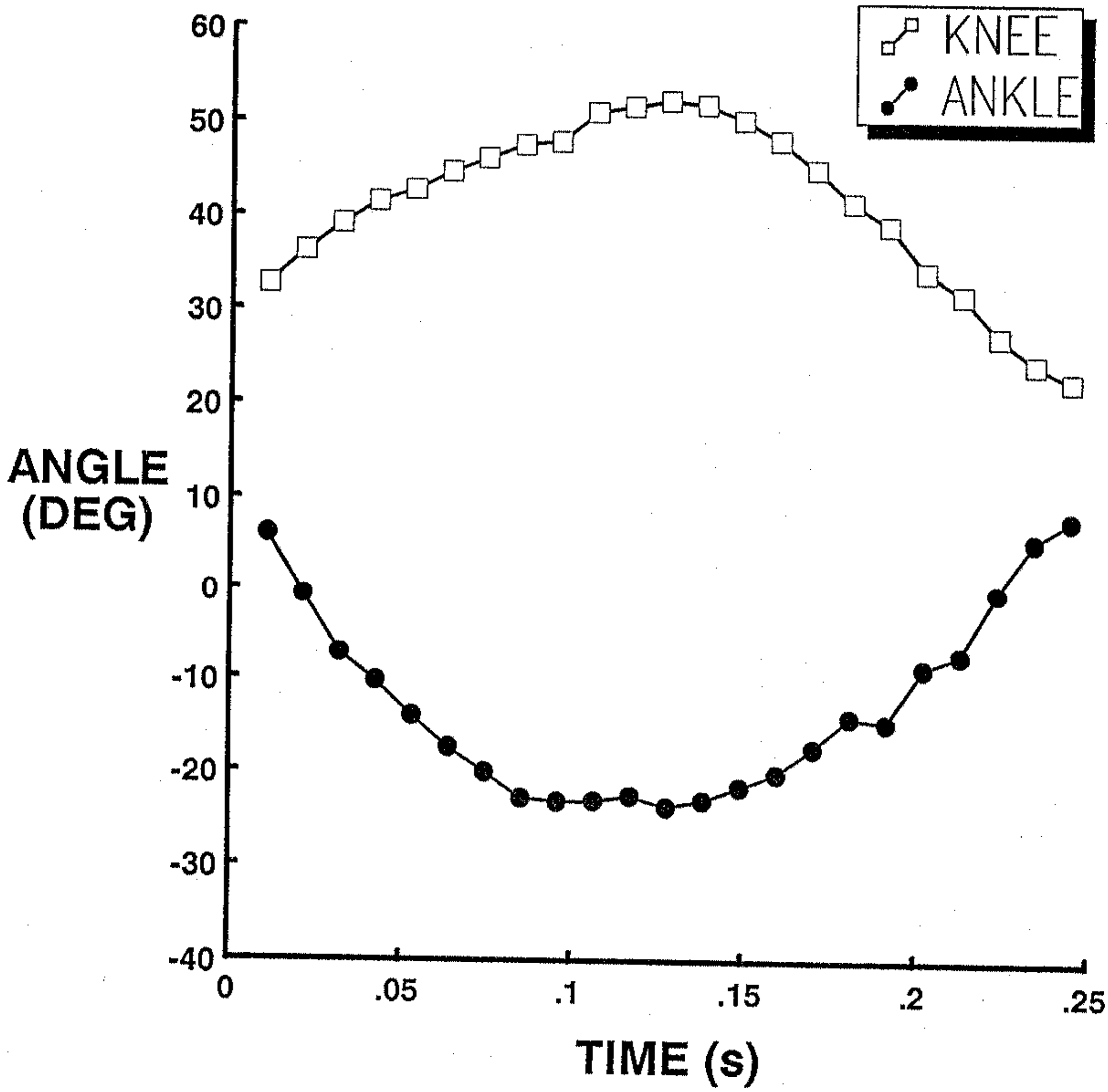

Fig. 21. Joint motions for Subject 3, Condition 2

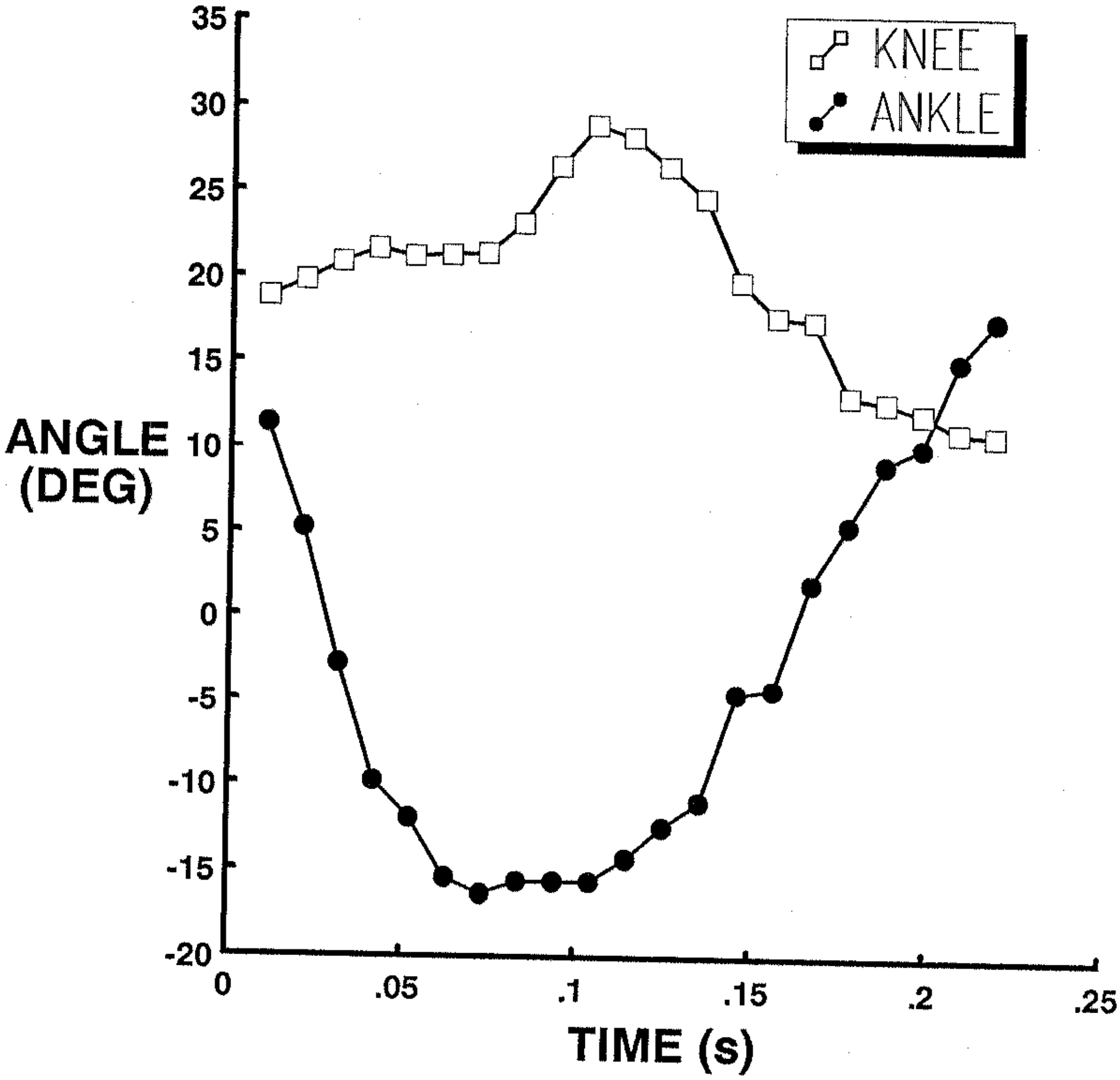

Fig. 22. Joint motions for Subject 4, Condition 2

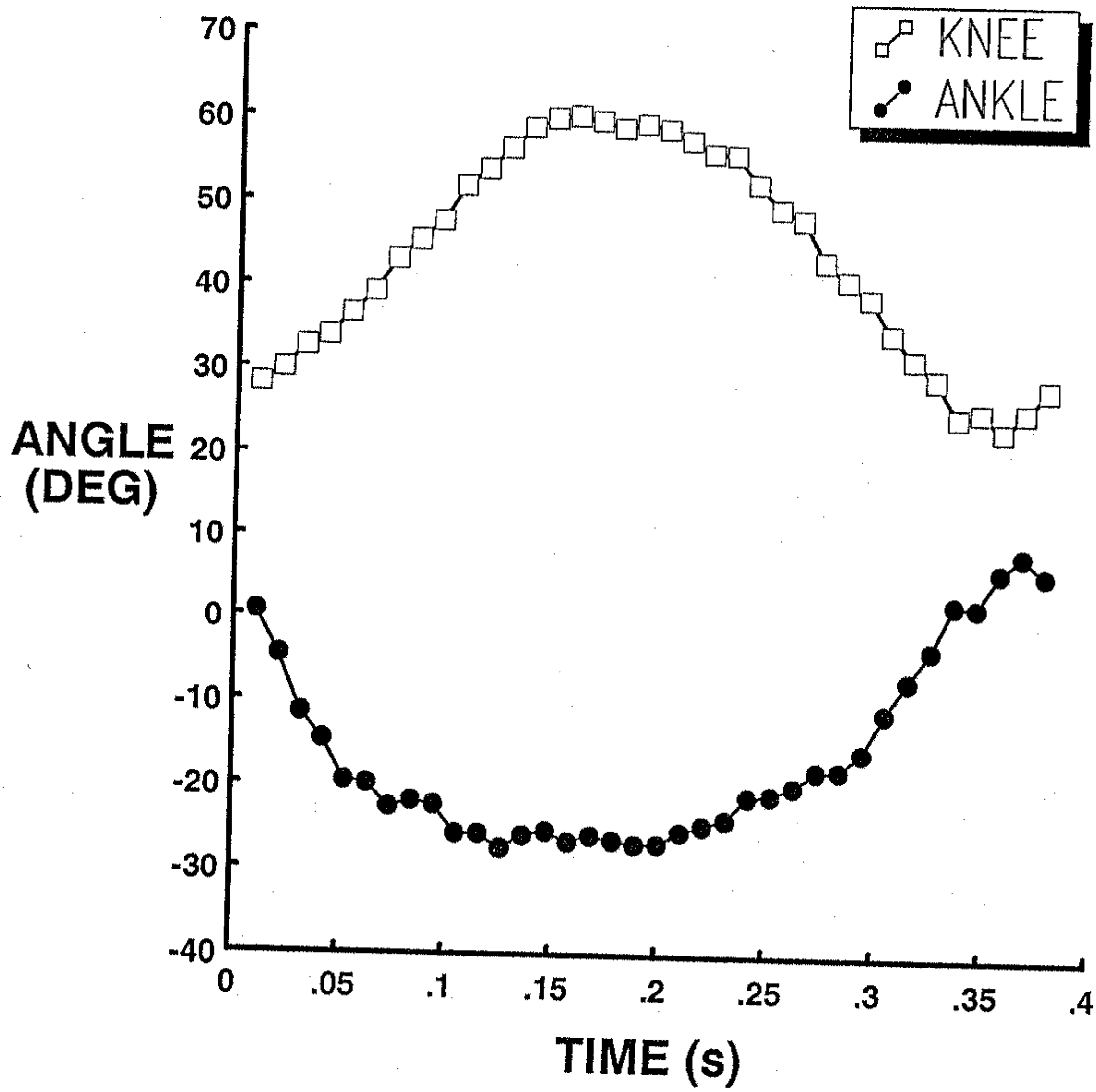

Fig. 23. Joint motions for Subject 9, Condition 2

Table 14

Mean and Standard Deviations of the Dependent Variables

Variable	Condition 1	Condition 2		
	Rhythm Bounce	Single Bounce	Jogging	Rhythm Bounce
F_z(BW)	2.076	2.429	2.251	2.003
	(±.622)	(±.44)	(±.388)	(±.91)
F_z Time-to-Peak (s)	.087	.11	.142	.081
	(±.011)	(±.028)	(±.047)	(±.066)
F_y (BW)	.433	.327	.444	1.082
	(±.276)	(±.138)	(±.476)	(±.749)
F_x (BW)	.332	.386	.482	.505
	(±.232)	(±.052)	(±.283)	(±.304)
Moments - Ankle (N.m)	73.402	75.846	67.659	107.91
	(±44.186)	(±49.119)	(±48.23)	(±67.46)
Time - Ankle (s)	.092	.102	.109	.083
	(±.012)	(±.012)	(±.006)	(±.009)
Moments - Knee (N.m)	161.764	148.939	121.048	273.308
	(±84.544)	(±89.701)	(±34.795)	(±119.273)
Time - Knee (s)	.095	.075	.12	.058
	(±.012)	(±.039)	(±.035)	(±.042)

used to find any relationship that might exist between a selected variable over both conditions.

The ANOVA showed no significant difference between Condition 1 and Condition 2 for any of the tested variables at the significance level of .001. This was tested for the 6 subjects who performed the single bounce and jogging styles in Condition 2. This did not include Subject 5 as there were no impacts analyzed in Condition 1 for this subject.

The individual styles were not analyzed within and across conditions as the sample size of the subjects to be analyzed ranged from 2 to 4 subjects, too small for any meaningful statistical analysis.

The ANOVAs were calculated using the StatView program written in 1985 and used on a Macintosh SE computer. (No other information was given by the company providing this program.)

CHAPTER V

SUMMARY, DISCUSSION, AND CONCLUSIONS

Summary

Impact variables are quantitative sources for addressing the amount of stress exerted upon a part of the body. Ground reaction forces, joint moments, and joint motion which represent variables commonly associated with impact, have not been examined for rope skipping. However, several aspects of impact loading, especially in jumping, have been examined.

Technique, influence of dropping height, and the parameters seen in attentuation of impact forces upon landing have been presented in different studies (Bobbert, Huijing, & Ingen Schenau, 1987a, 1987b; Coleman, Adrian, & Yamamoto, 1984; Lees, 1981; Mizrahi & Susak, 1982). Impact landings as applied to basketball rebounds have also been examined (Valiant & Cavanagh, 1985).

The aerobic aspects of rope skipping have been examined in detail over several variables. Different styles and cadences have been analyzed as to their effect on HR and $\dot{V}O_2$ (Myles, Dick, & Jantti, 1981; Getchell & Cleary, 1980; Jette, Mongeon, & Routhier, 1979; Quirk & Sinning, 1982; Town, Sol, & Sinning, 1980).

The physiological component of rope skipping has received more attention than the biomechanical nature of the activity. Both components are needed to help determine the potential benefits and dangers of rope skipping as exercise. Therefore, the purpose of this study was to measure ground reaction forces under one foot and compute the net moments about the ankle and knee during different styles and rates of rope skipping.

Eight males and 2 females skipped rope for two separate 5 minute sessions. One session was denoted as Condition 1, where each subject maintained a nominal skipping rate of 80 turns/min while utilizing the rhythm bounce style. The other session was designated as Condition 2, where the subjects chose their own style and rate of skipping. Four subjects chose the single bounce style; three chose a jogging style, while the rhythm bounce was the preferred style for the other three.

Filming and force plate data were taken at the end of each session for approximately 3 to 4 seconds. Six points were digitized from each frame of film and smoothed with the Quintic Spline smoothing technique. Digitized coordinates were utilized to compute segmental and joint kinematics. The ground reaction forces in the vertical, anterior-posterior, and medial-lateral directions were recorded directly from the force plate and then converted to Newtons and further divided into units of body weight. The film data and force plate data were combined to calculate the moments about the ankle and knee.

Two consecutive impacts, one primary and one secondary, were chosen in Condition 1 as representative of that trial for each subject for further analysis. Subject 5 had no usable impacts in this condition. One impact was chosen for each subject in Condition 2.

Previously reported were the ranges, means, and standard deviations for:

1. peak vertical (F_z) GRF;
2. time-to-peak for F_z;
3. peak F_x;
4. peak F_y;
5. peak ankle and knee moments;
6. time-to-peak for ankle and knee moments.

The force-time curves and time histories for the moments were described. The joint angles of the ankle and knee were also presented.

Statistical analysis determined no significant difference between Condition 1 and Condition 2 for peak F_z, moments about the ankle, and moments about the knee.

Discussion

Discussions of previously reported data are presented in this chapter. Comparisons to values obtained in other studies related to impacts in jumping are also made. Finally, conclusions derived from this study and suggestions for further study are made.

Comparison to Literature

The mean peak vertical forces reported in this study ranged from 2.003 BW ($\pm$ .91 BW) for the rhythm bounce group in Condition 2 to 2.429 ($\pm$ .44 BW) by those performing the single bounce style in Condition 2. These impacts could be characterized primarily as soft landings for the right lower extremity according to Lees (1981). One parameter of the hard versus soft landing was F_z in terms of BW. Peak F_z in hard landings were greater than 3 BW while peak F_z in soft landings were 2 BW.

The mean F_z for the different styles and conditions was less than the peak mean vertical forces reported in other jumping studies. Drops from .5 m and 1 m produced a range of peak forces from 2.47 BW to 6.55 BW (Mizrahi & Susak, 1982 - no standard deviations presented). Peak impacts resulting after rebounding a basketball ranged from 4.1 BW to 6.0 BW (Valiant & Cavanagh, 1985).

Although the peak vertical forces in rope skipping were less than the other forces reported, the height of the jump during skipping was not measured or controlled. Also, the other studies measured only impact with the subjects coming to rest upon the force plate. They did not include a subsequent rebound and airborne phase. Lees (1981), Mizrahi and Susak (1982) measured impact under both feet, while Valiant and Cavanagh measured under the right foot (1985).

Using a different point of reference, the peak vertical forces seen in rope skipping in this study were similar to those reported for jogging utilizing a one foot impact. Cavanagh and LaFortune reported forces of 2.2 BW (± .4 BW) to 2.8 BW (± .3 BW) in rearfoot and midfoot jogging styles (1980). Munro and Miller reported forces at 1.6 BW for a jogging speed at 3 m/s and 2.3 BW at 5 m/s (1987 - no S. D. reported).

The time-to-peak of F_z was variable across the styles. The rhythm bounce style produced a mean time-to-peak of .081 s (± .006 s) by the 3 subjects in Condition 2 and .087 s (± .011 s) in Condition 1. The jogging style produced the longest mean time-to-peak of .142 s (± .047 s) and the single bounce mean was .11 s (± .028 s). The differences seen may be attributed to the different styles. The total time of the impact phase of the jogging style was longer than any other style. Therefore, it was not unusual that the time-to-peak was longer. The skipping rates for the single bounce ranged from 74 to 141 turns/min. With the single impact, the time on the force plate was dependent upon the skipping rate. The range from slow-to-fast would average to a moderate total impact time. In the rhythm bounce, there were two impacts to a single turn of the rope. At a similar rate, it was not surprising that the two means were similar over both conditions. With two impacts per turn, the total impact time would be shorter than for a single impact at the same or similar skipping rate.

The means presented for the rope skipping styles are longer than the time-to-peak of F_z found in rebounding. The range reported by Valiant and Cavanagh was .012 s for flatfooted landings and .037 s for forefoot landings (1985). The times-to-peak for the other impact studies were not reported although Lees presented times-to-peak in his methods of absorption. Both hard and soft landings were characterized by times-to-peak of approximately .1 seconds.

All subjects in both conditions produced reaction forces in the medial-lateral and anterior-posterior directions. Except for Subject 6 in Condition 2, all peak forces in these directions were less than 1 BW. The mean values of these forces were not reported in most studies in the related literature. The only jumping study that reports any other GRF other than F_z was the study examining basketball rebounding. Valiant and Cavanagh reported that only 3 out of 10 subjects had any laterally-directed force (1985). The peak was about .25 BW. The anterior-posterior recordings were not reported. These forces were described in the jogging study by Cavanagh and LaFortune (1980). F_x was different for the rearfoot and midfoot strikers at .12 BW and .35 BW respectively. The F_y forces recorded were .43 BW (± .05 BW) for the rearfoot group and .45 BW (± .09 BW) for the forefoot group.

The jogging style in Condition 2 had the lowest mean peak ankle and knee moments, while the subjects performing the rhythm bounce style in Condition 2 had the highest. The range for the ankle was 67.659 N.m (± 48.32 N.m) to 107.91 N.m (± 67.46 N.m). The knee range was 121.048 N.m (± 34.795 N.m) to 273.308 N.m (± 119.273 N.m). These values are below the values presented by Bobbert, Huijing, and Ingen Schenau in their examination of drop jumping (1987a, 1987b). The ankle means reported ranged from 310 ± 50 N.m by the countermovement jump to 602 ± 165 N.m for bounce drop jumps, both from the first study. The means for the knee moments ranged from 366 ± 64 N.m for the countermovement jumps to 588 ± 146 N.m for the bounce drop jumps. The values reported in the second study for drop jumps from different heights fell within the ranges given for the first study for both the ankle and knee. The two studies included both an impact and push-off phase with force contact made by both feet.

In an additional study examining coordination in vertical jumping, Bobbert and Ingen Schenau reported mean peak ankle moments of approximately 300 N.m and mean peak knee moments between 300 and 350 N.m (1988). Actual values were not reported. The mean moments were presented on graphs. This study examined only the push-off phase. It did not include an impact phase upon foot strike.

The mean peak ankle moments were less than the mean peak knee moments across all styles and conditions of rope skipping. This was consistent with the values reported in the drop jump studies.

The other jump studies and running studies reviewed did not calculate joint moments. The time-to-peak was also not examined by any of the studies reviewed, although the sequencing of the peak moments were discussed.

Condition 1

Although all the subjects were performing the same style at approximately the same rate, the results presented differed between subjects. Subjects 1, 3, and 7 had similar peak F_z. However, as Figures 24, 25, and 26 demonstrate, there were differences in their force-time curves. There were also differences in their peak moments. Subject 7 had a steeper slope in F_z, but a longer duration of the higher magnitudes near the peak value.

There were no similarities in the magnitudes of the peak ankle or peak knee moments between these three subjects. The moment-time curves for Subjects 1 and 3 were similar with the ankle following the same pattern as the knee, but with much less magnitude. (See Figure 12 - Subject 3.) Subjects 1 and 3 also had a distinct rise to peak moment with a quick

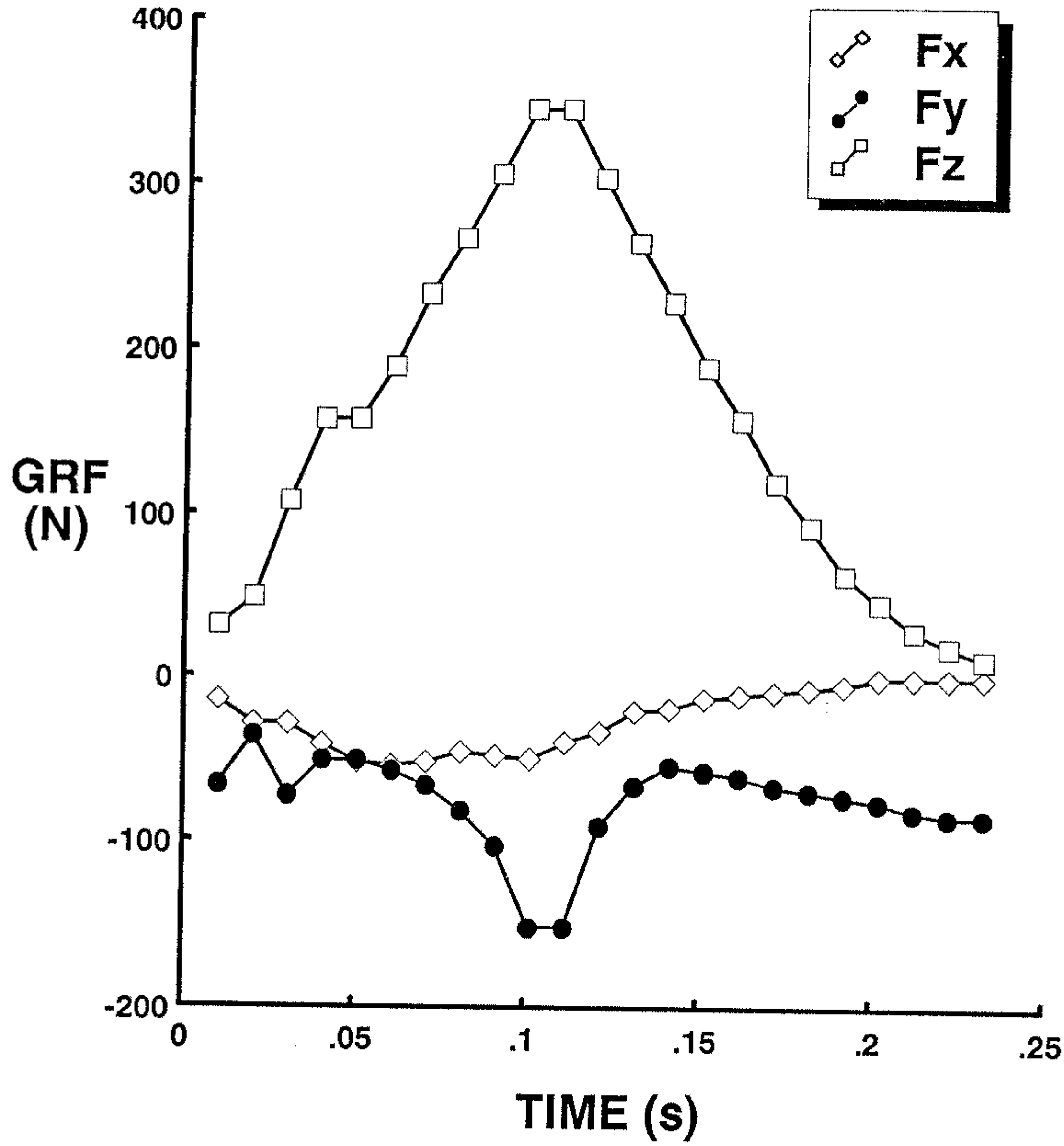

Fig. 24. Force-time curve for Subject 1 in Condition 2

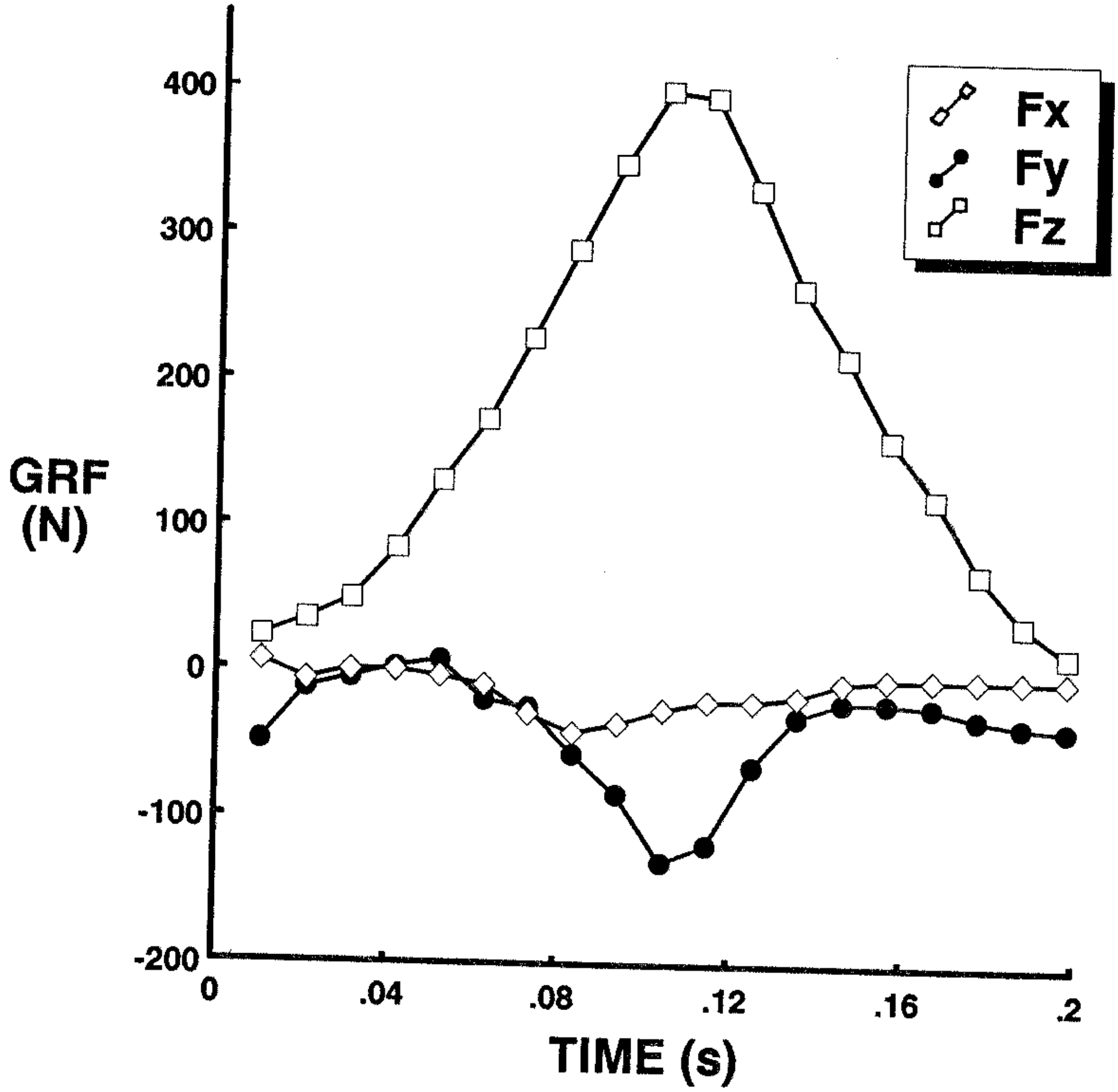

Fig. 25. Force-time curve for Subject 3 in Condition 2

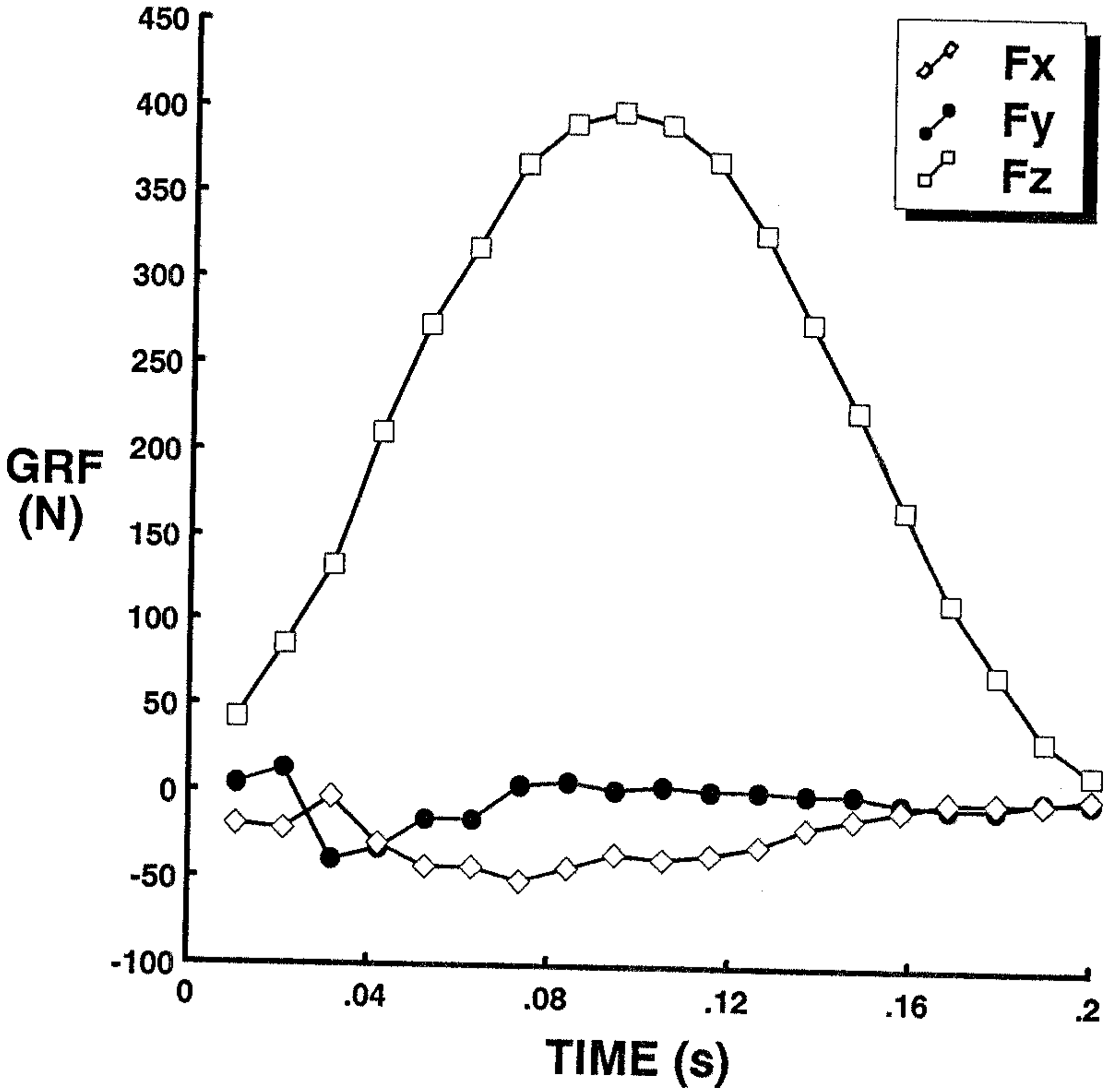

Fig. 26. Force-time curve for Subject 7 in Condition 2

decline. Subject 7 had a less distinct peak with multiple changes in direction of the knee moments. (See Figure 27.)

The differences observed carry over to the joint movement at the ankle and knee recorded by the 3 subjects. Figures 14a, 28a, and 28b present the joint motions for Subjects 3, 1, and 7 respectively. Subject 1 demonstrated little knee flexion or ankle dorsiflexion upon impact. Subject 1 had the highest peak ankle and knee moments for this condition. The lack of dissipation of the impact through joint motion may account for the large moments even though the peak F_z was approximately the same as Subjects 3 and 7. Subject 3 had some initial knee flexion with ankle dorsiflexion while Subject 7 demonstrated greater knee flexion than either subject in addition to ankle dorsiflexion. Subject 7 had less ankle and knee moments than either Subject 1 or Subject 3.

The distribution of the stress of impact was taken predominantly in the knee for all 3 subjects. The peak knee moment corresponded with the peak F_z as well as a decrease or no further increase in knee flexion in Subject 1 and 3. The difference between the ankle and knee moments for Subject 7 was less than for Subjects 1 and 3, but the knee moments were more variable in direction for Subject 7.

Subjects 2 and 6 also demonstrated how the GRF could be similar yet the moments were different. The force-time curves were similar in appearance with a quick rise to peak,

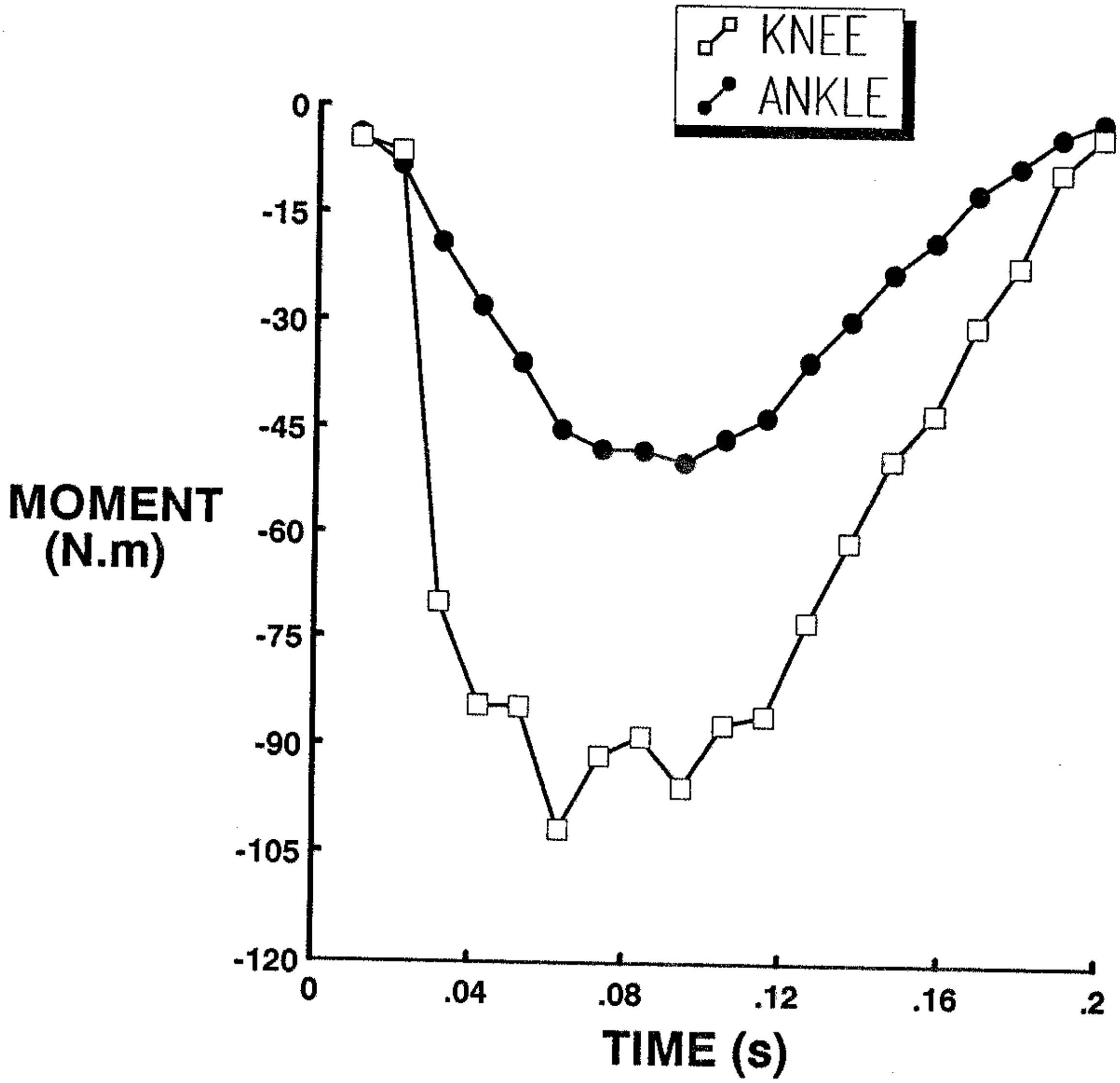

Fig. 27. Moment-time curve for Subject 7, Condition 1

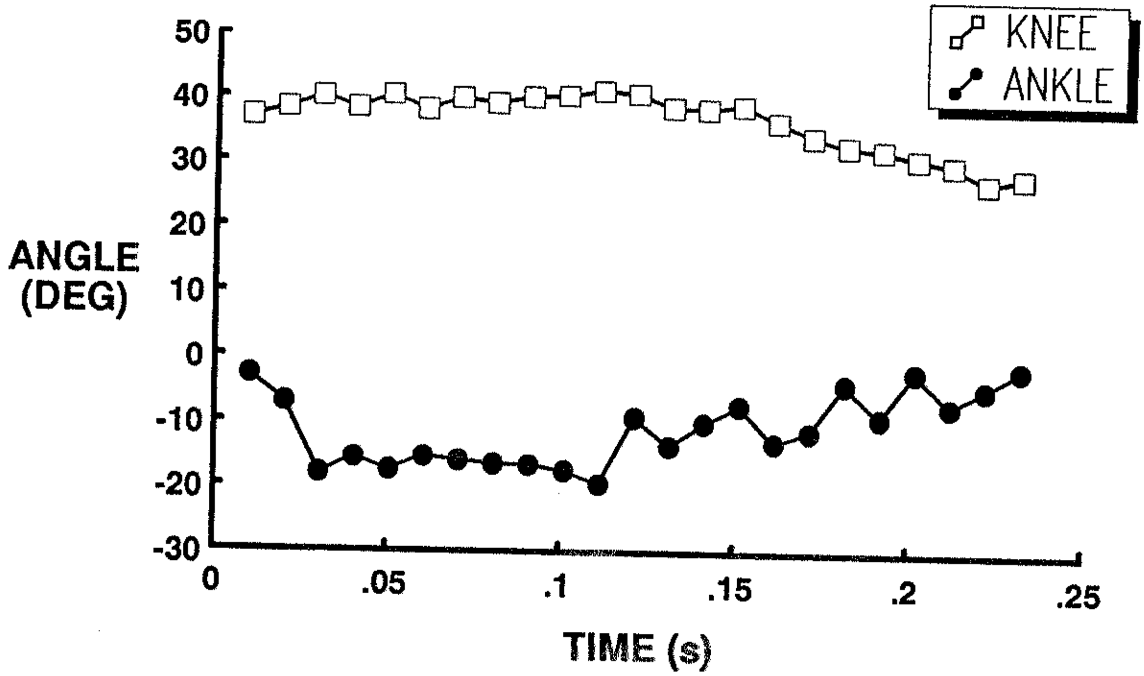

Fig. 28a. Joint motions for Subject 1, Condition 1

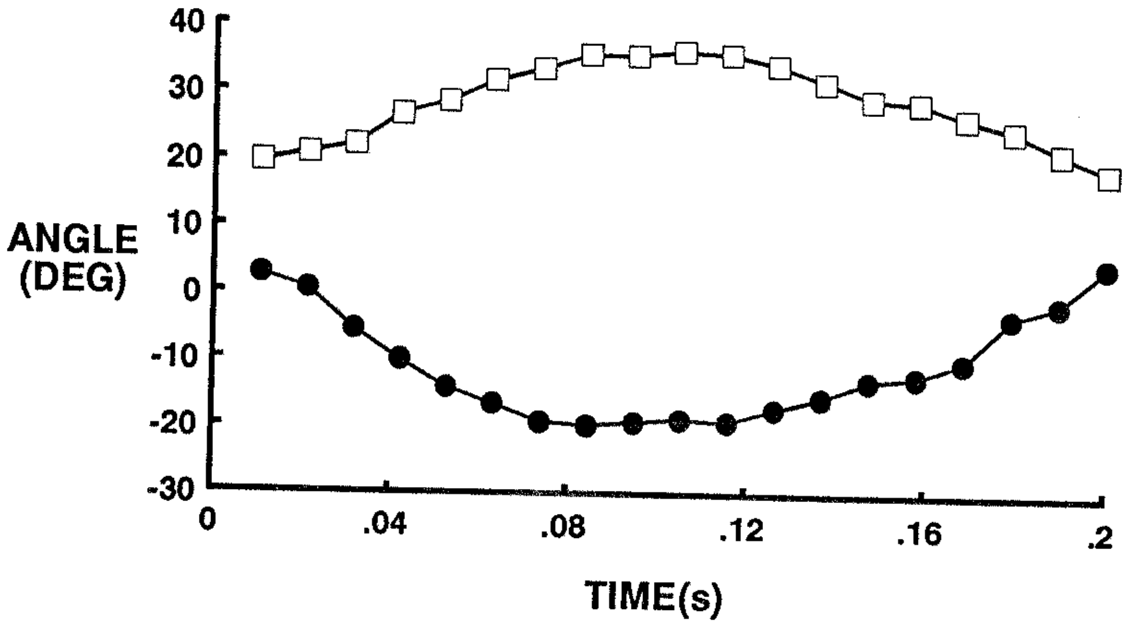

Fig. 28b. Joint motions for Subject 7, Condition 1

then a gradual decline. (See Figure 10a, Subject 2.) Although the magnitude of the ankle and knee moments was greater for Subject 2, the coordination and sequencing of movement were better for Subject 2 than for Subject 6. As Figure 11 demonstrates, the magnitude and direction of the joint moments closely approximated synchronization for Subject 2. Subject 6 had lesser magnitudes, but little coordination between the ankle and knee with the knee moments more variable in magnitude and direction than the ankle. (See Figure 29.)

Subjects 9 and 10 had the lowest peak F_z in this condition. Figure 30 is the force-time curve for Subject 9. The force-time curve for Subject 9 differed from the other subjects' curves in that after the peak, a gradual decline began, but then flattened out before resuming the decline. The fairly rapid rise to peak with the different decline from peak combined with knee flexion upon impact, produced a large knee moment spike. Otherwise, the ankle and knee moments were close in magnitude and direction. Subject 10 also demonstrated a small range of ankle moments with greater knee moments. (See Figures 31a, 31b.)

Subject 8 presented the best pattern of motion observed during the primary impact. Although the peak F_z was the next to the highest, the dissipation across the articulations and the sequencing of movement was better than for the other subjects. As observed in Figure 32a, the force-time curve

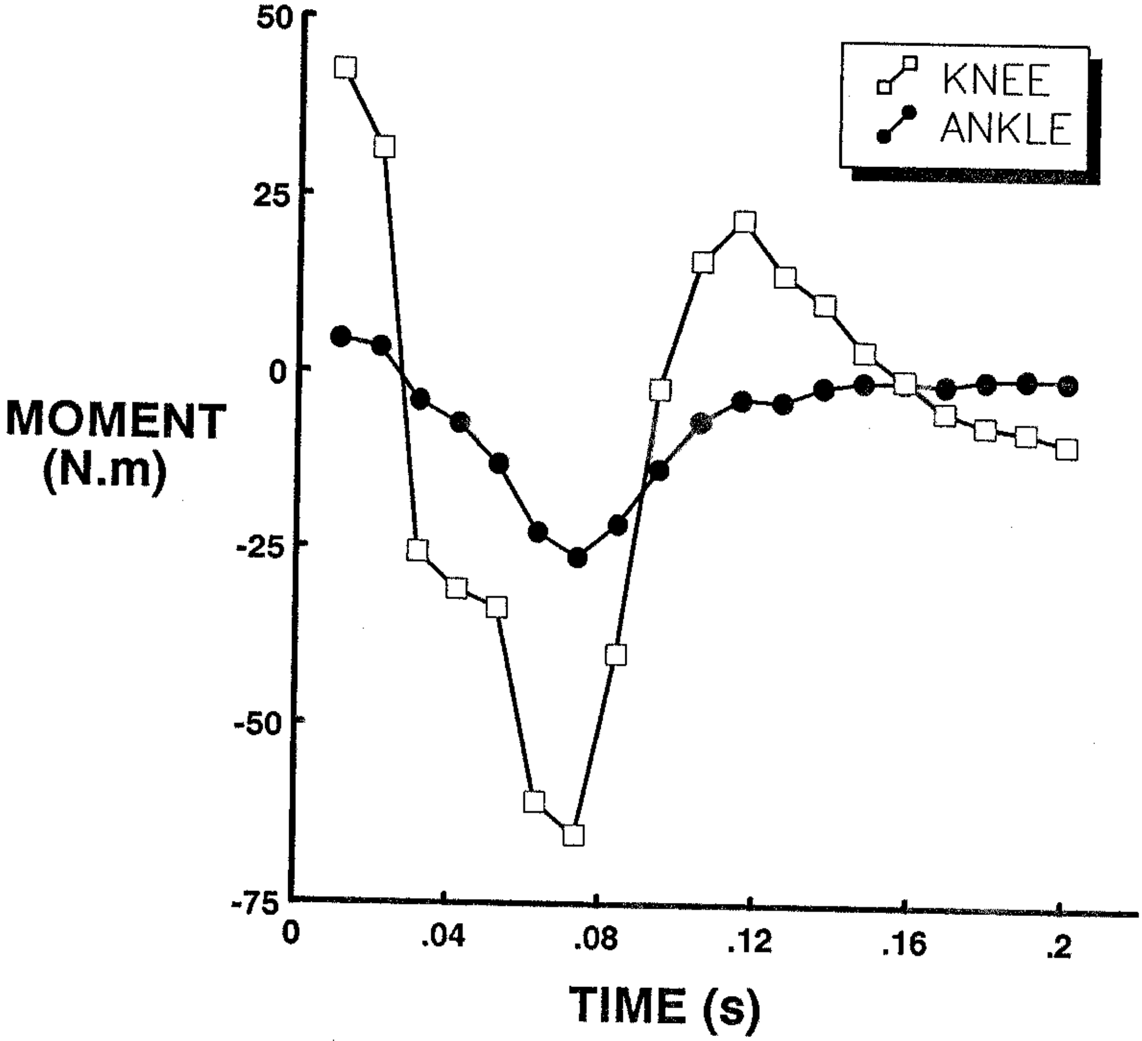

Fig. 29. Moment-time curve for Subject 6, Condition 1

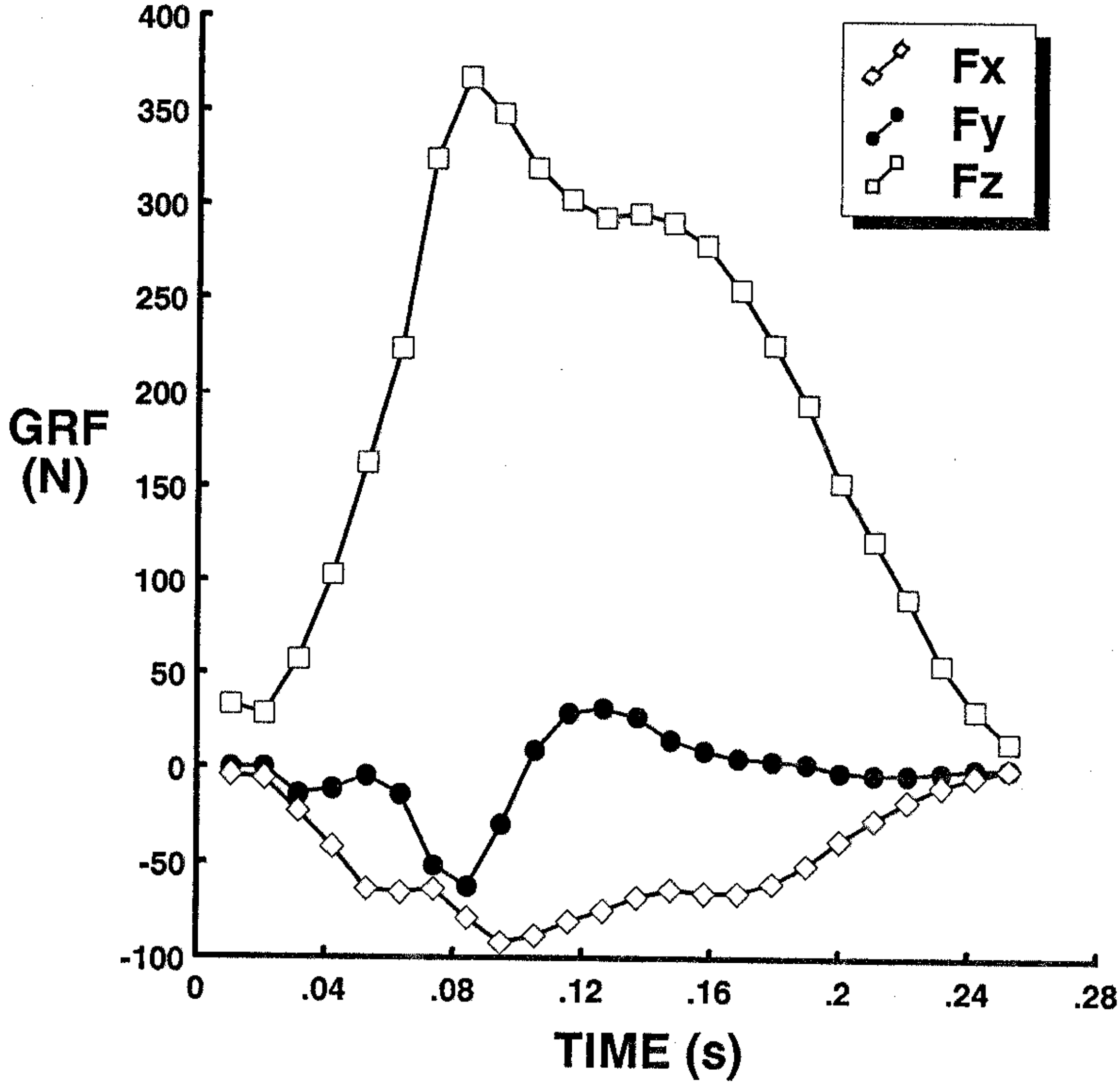

Fig. 30. Force-time curve for Subject 9, Condition 1

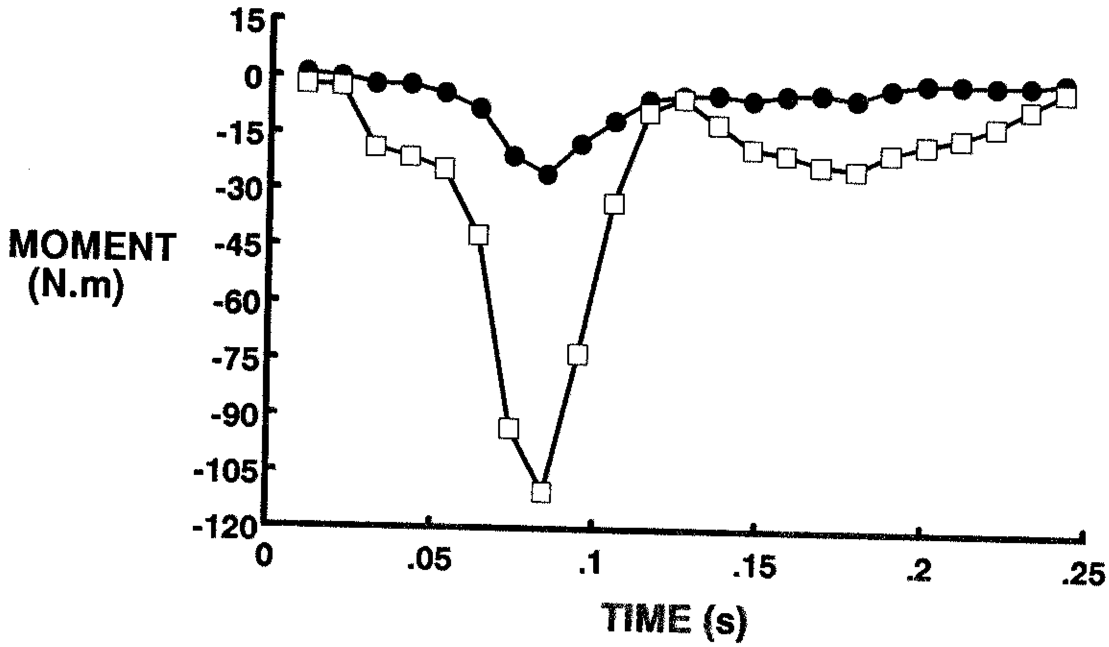

Fig. 31a. Moment-time curve for Subject 9, Condition 1

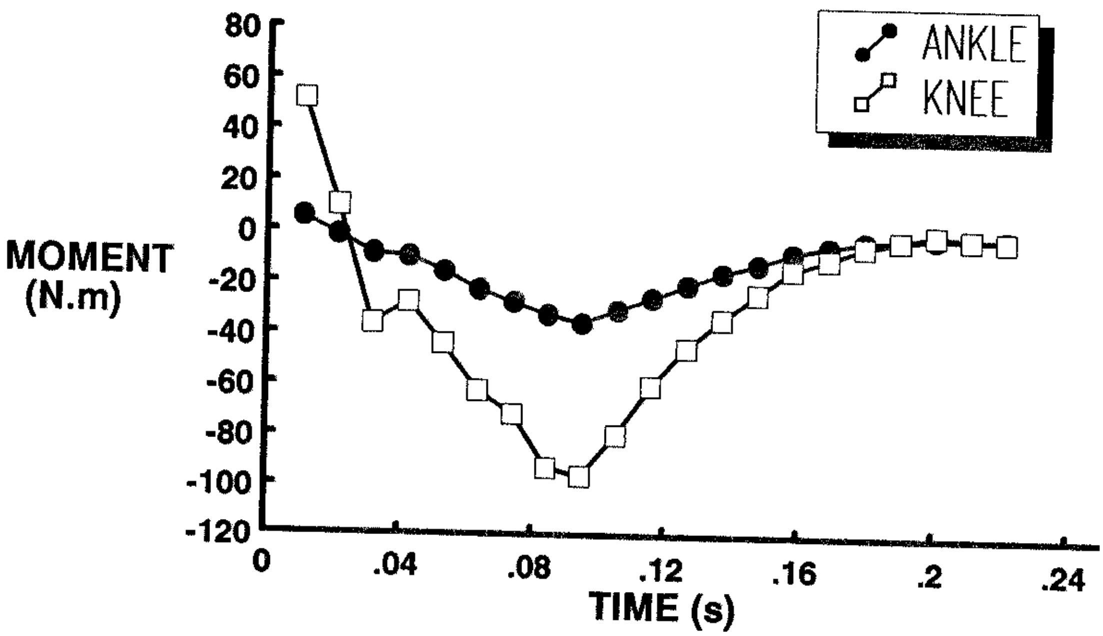

Fig. 31b. Moment-time curve for Subject 10, Condition 1

showed a gradual rise and decline with a rounded peak. The ankle and knee moments were similar in direction. The range of ankle moments across time was greater than for the other subjects. (See Figure 32b.) There was similarity in magnitude for the moments except at the peak where the knee moments were greater. The knee has a larger range of motion and longer moment arms, so this would not be unusual. There was gradual dorsiflexion and knee flexion upon impact followed by knee extension and plantarflexion in preparation for take-off. (See Figure 14b.)

Subject 4 presented the worst pattern of motion. This subject had the highest peak F_z with the shortest time-to-peak. A short time-to-peak does not allow for good dissipation of the impact forces, especially F_z. The ability to dissipate F_z was further lessened with little knee flexion. Figure 33 shows that although dorsiflexion began at the time of impact, knee flexion did not begin until peak F_z had been reached and then only lasted for approximately .04 s. The extension phase began about half-way through the impact with relatively large knee extension and plantarflexion motions. It is not surprising then, to observe in Figure 13, the flucuations in the knee moments in both direction and magnitude. Although some activity was occurring about the ankle, the range of ankle moments was small compared to the knee, and the ankle moments did not follow the same pattern as the knee. This subject was taking the stress of the impact at the knee.

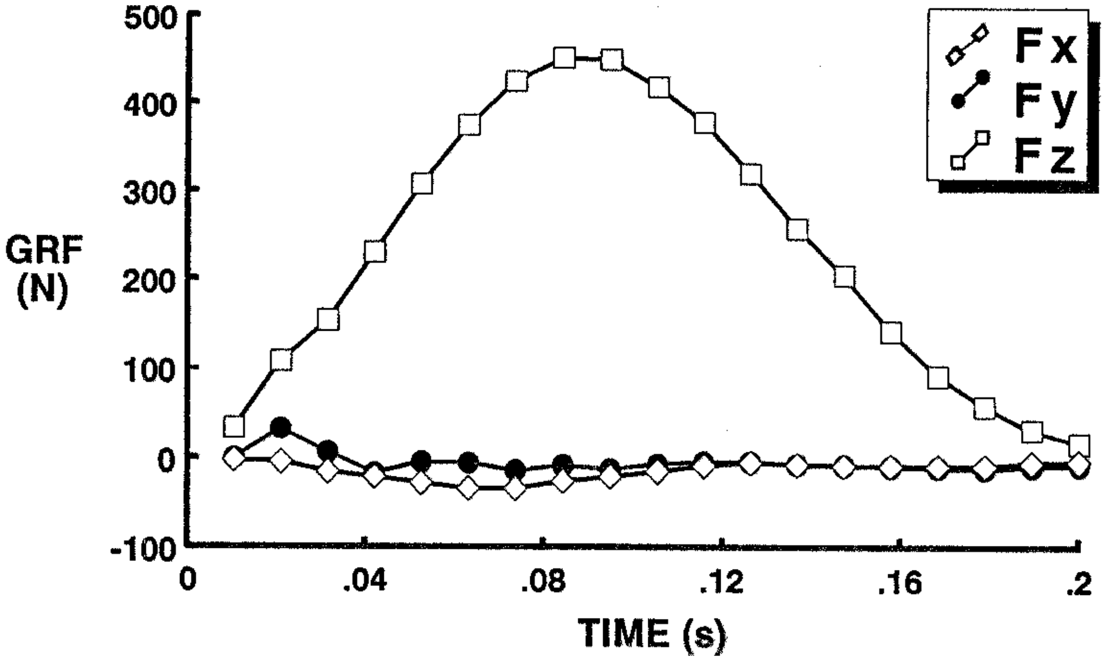

Fig. 32a. Force-time curve for Subject 8, Condition 1

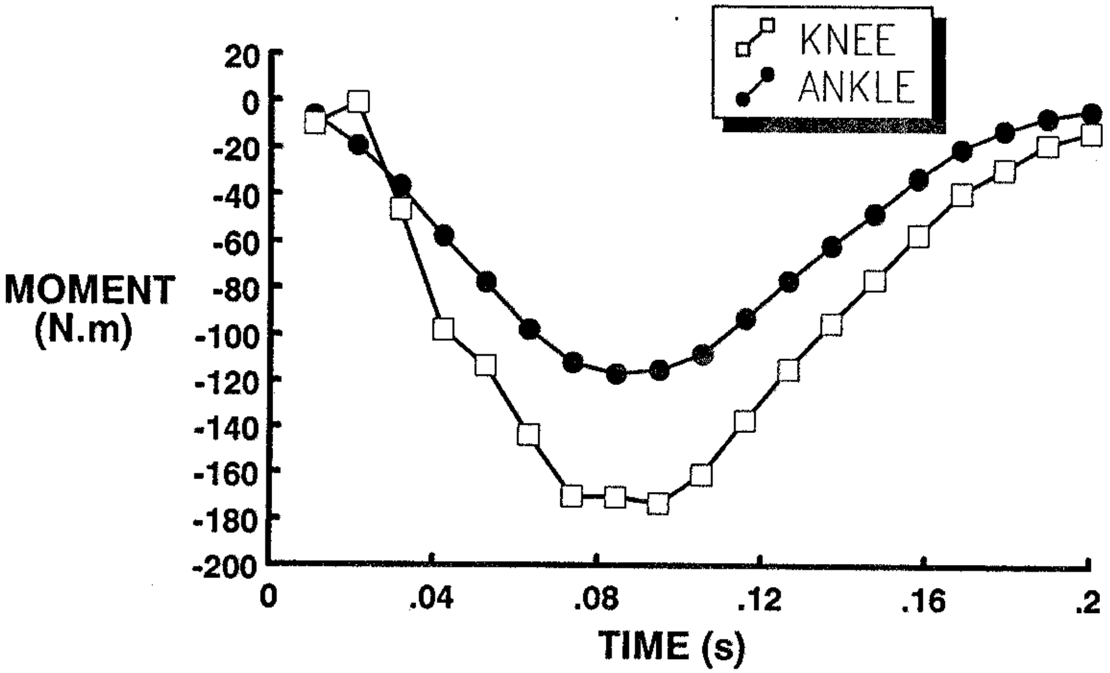

Fig. 32b. Moment-time curve for Subject 8, Condition 1

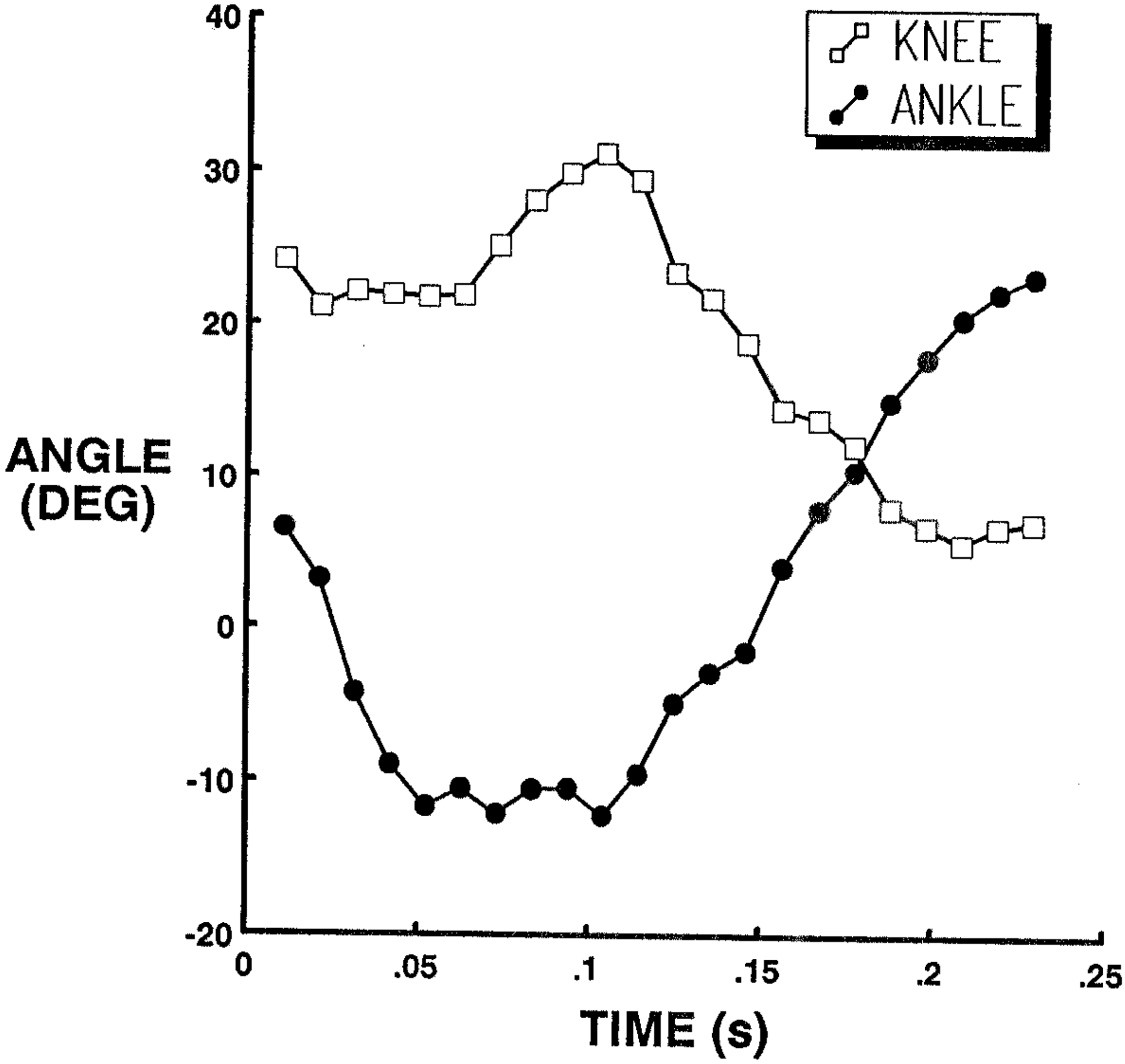

Fig. 33. Joint motions for Subject 4, Condition 1

The secondary impacts were generally more consistent across all variables. The force-time curves demonstrated the same pattern with a gradual rise to peak followed by a gradual decline. However, Subject 4 demonstrated a very steep rise to peak and a long duration at peak followed by a gradual decline (Figure 34). The moments generally approximated each other in direction and magnitude indicating a better distribution of forces across the articulations. As observed in Figure 35a, Subject 3 demonstrated more of a spike in the knee moments with a greater difference between the ankle and knee moment magnitudes. As with the primary impact, Subject 4 had variability in direction and magnitude of the moments, with the knee taking the greater stress. (See Figure 35b.) Again, little knee flexion was apparent, with extension dominating the impact phase.

The force-time curves for the secondary impact generally demonstrated a negative skewness, while the primary curves were generally skewed positively. Subjects 2, 3, 4, 8, and 9 showed the same general pattern for the ankle and knee moment curves in the secondary impacts as they did for the primary impacts.

Condition 2

Single Bounce

There were few similarities between the subjects in the variables analyzed. The shape of the force-time curves was

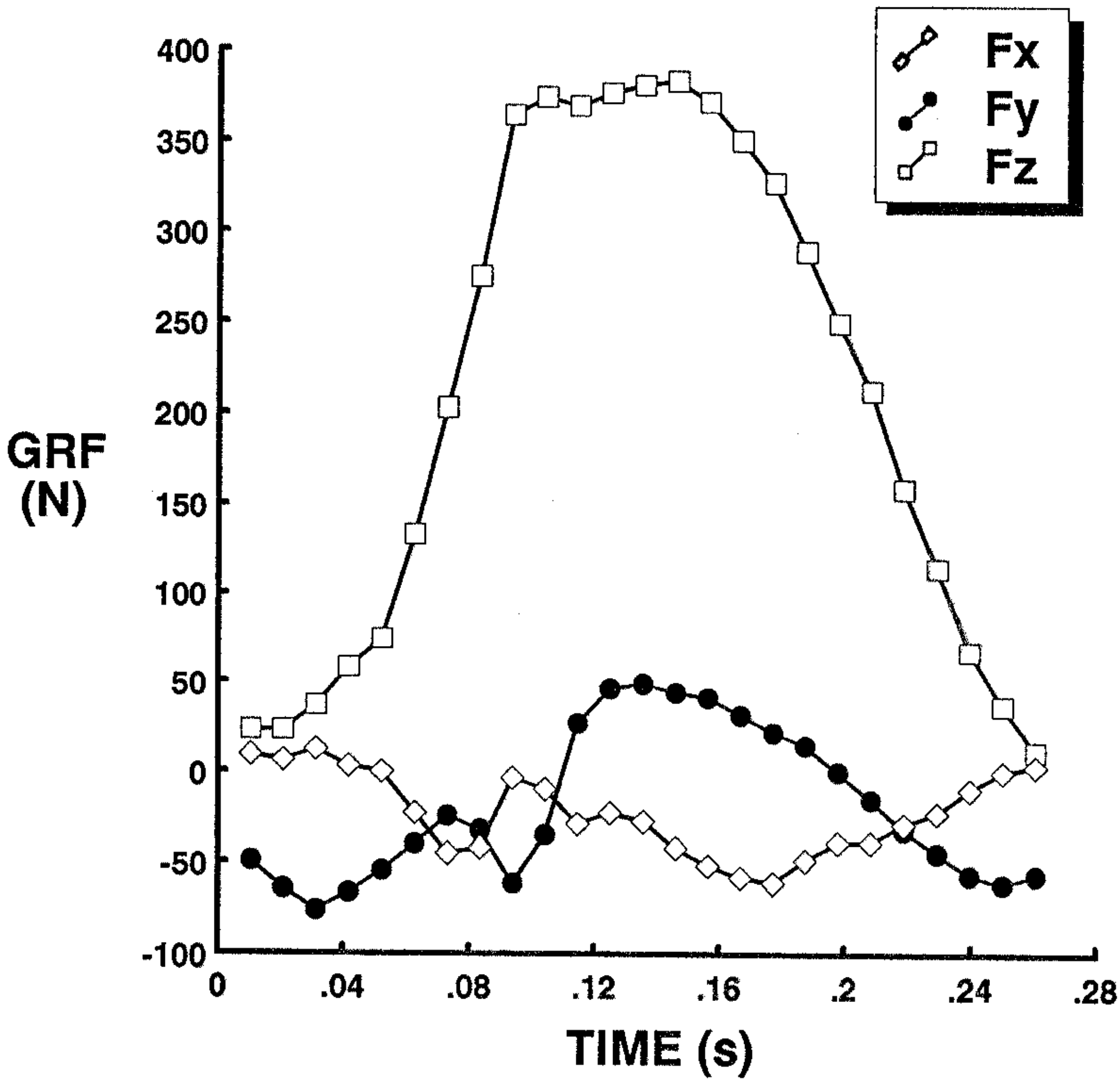

Fig. 34. Force-time curve for Subject 4, Condition 1, Secondary impact

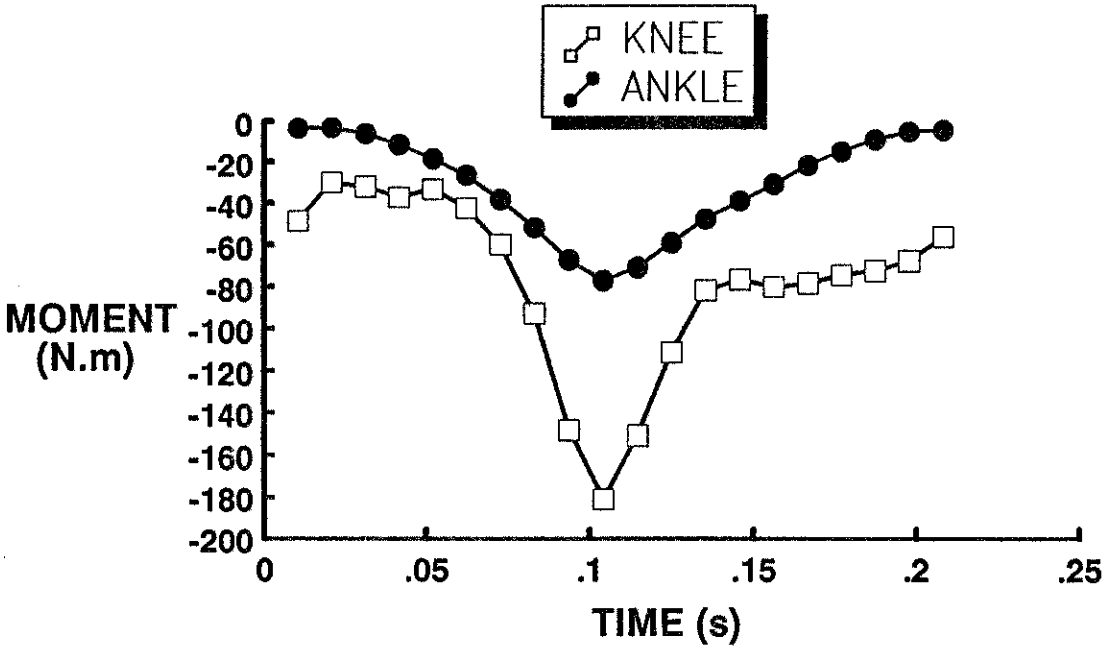

Fig. 35a. Moment-time curve for Subject 3, Condition 1, Secondary impact

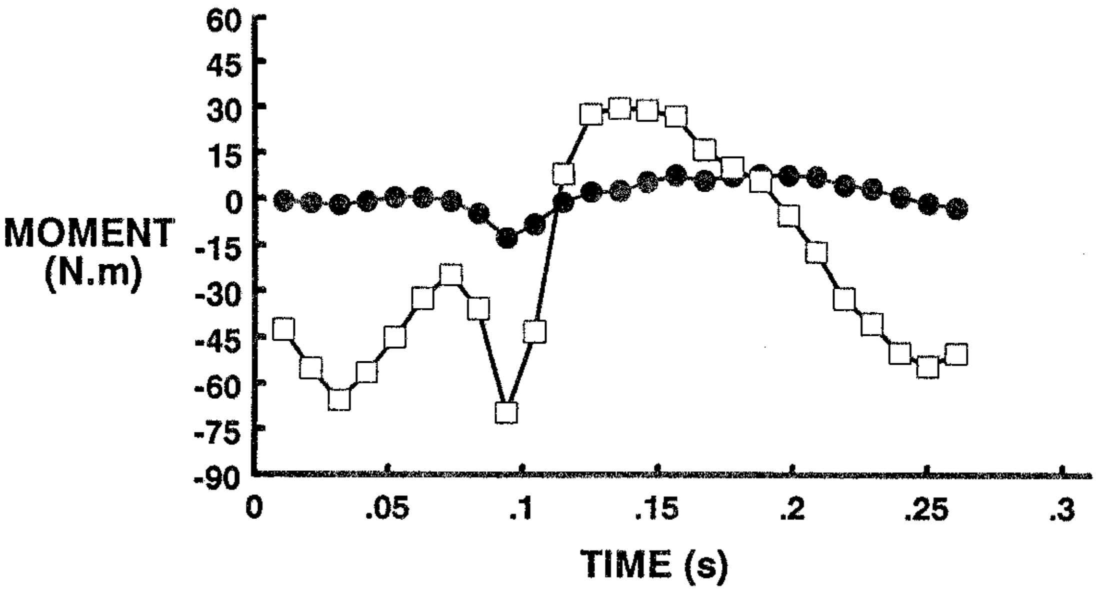

Fig. 35b Moment-time curve for Subject 4, Condition 1, Secondary impact

similar in slope and duration of the upper magnitude values near the peak and peak values. Figure 15 demonstrates the shape of the curve that is representative of this style. Subjects 1 and 7 had similar peak F_z at similar time-to-peak F_z. Subject 3 had the longest time-to-peak of .12316 s that corresponded with the lowest peak F_z. Subject 8 had the shortest time-to-peak and the largest peak F_z. As previously mentioned, a shorter time-to-peak generally results in a higher peak F_z. The opposite is also true. A longer time-to-peak can produce a lower F_z. Subject 3 had a longer time in which to dissipate F_z. The skipping rate did not appear to influence the timing of peak F_z, as Subject 1 had the slowest rate at 74 turns/min, while Subject 7 had the highest at 141 turns/min. Subjects 3 and 8 had similar rates, 120 and 127 turns/min respectively.

Subject 3 also had the lowest peak ankle moment and a low peak moment. However, as Figure 20b demonstrates, most of the stress was placed on the knee. Little rotary activity happened at the ankle. The knee pattern was erratic with several changes in direction and magnitude of the moments. A more efficient pattern would be the ankle and knee acting in synchrony in direction and close in magnitude.

Subject 7 also had an erratic knee moment pattern although the moments were relatively small. The ankle had higher moments than the knee but were smoother with less change in direction and gradual changes in magnitude. (See Figure 36.)

Subjects 1 and 8 presented a similar pattern in both the ankle and knee moments as represented in Figure 20a. The ankle and knee moments in both subjects were similar in magnitude and direction which demonstrated good sequencing of the ankle and knee. The stresses were distributed across both articulations. The peak knee moments were larger than the ankle in both subjects, which could be due to the differences in range of motion available and the lengths of the moment arms at the ankle and knee.

The joint motions produced at the ankle and knee were similar for Subjects 1, 3, and 7 as represented by Figure 21. Subject 1 had less knee flexion than the other two, which might account for the higher knee moments. Subject 8 had a completely different pattern (see Figure 37). There was a quick amount of dorsiflexion with little knee flexion followed by a fairly neutral phase with the rest of the contact phase showing knee extension and plantarflexion. The lack of knee flexion at impact might account for the high peak F_z and quick time-to-peak. The coordination of the movements of the ankle and knee during the impact phase might account for the coordination between the ankle and knee moments.

Although the magnitude of the peak F_z and peak moments were greater, Subjects 1 and 8 performed this style of rope

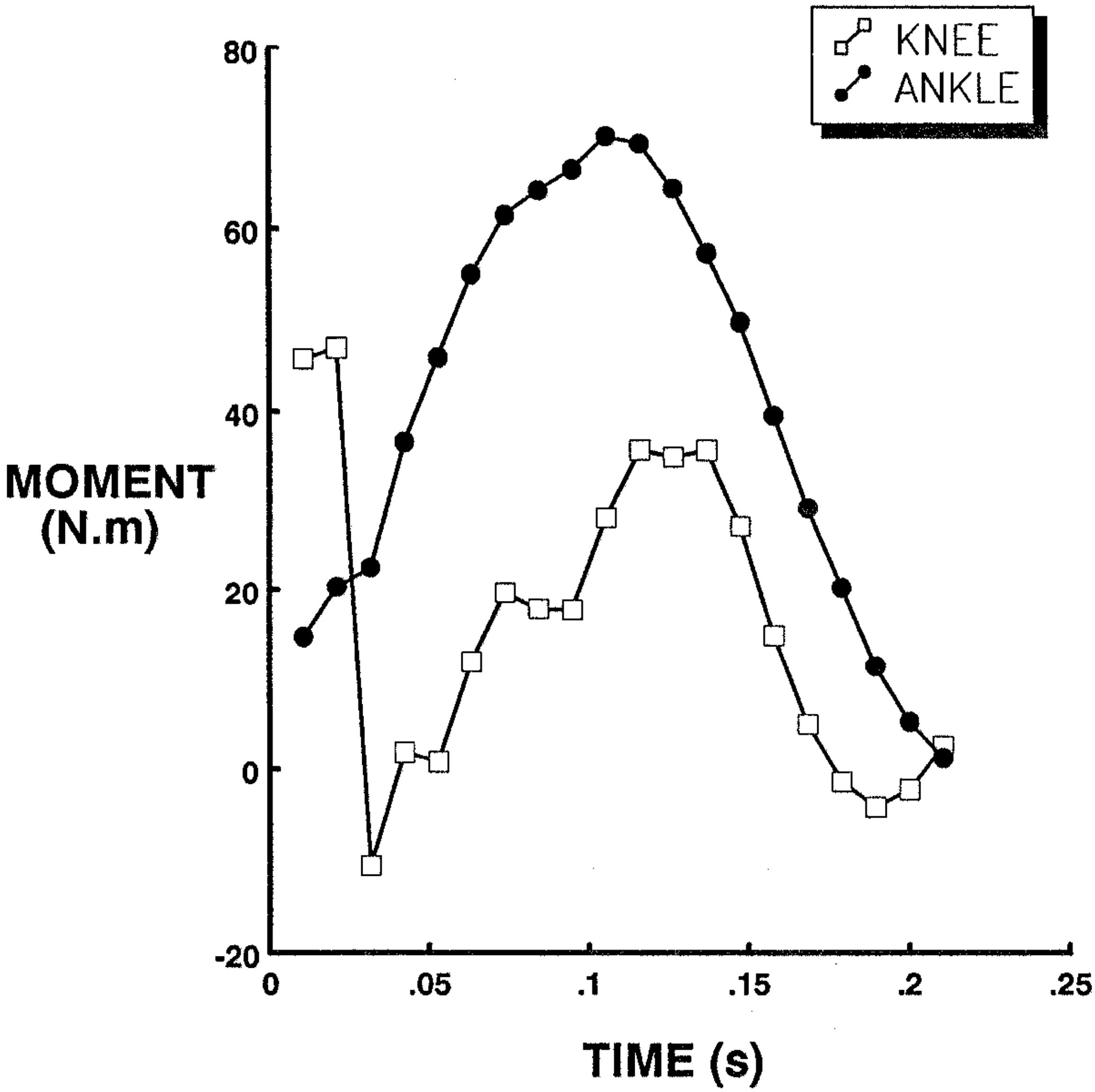

Fig. 36. Moment-time curve for Subject 7, Condition 2

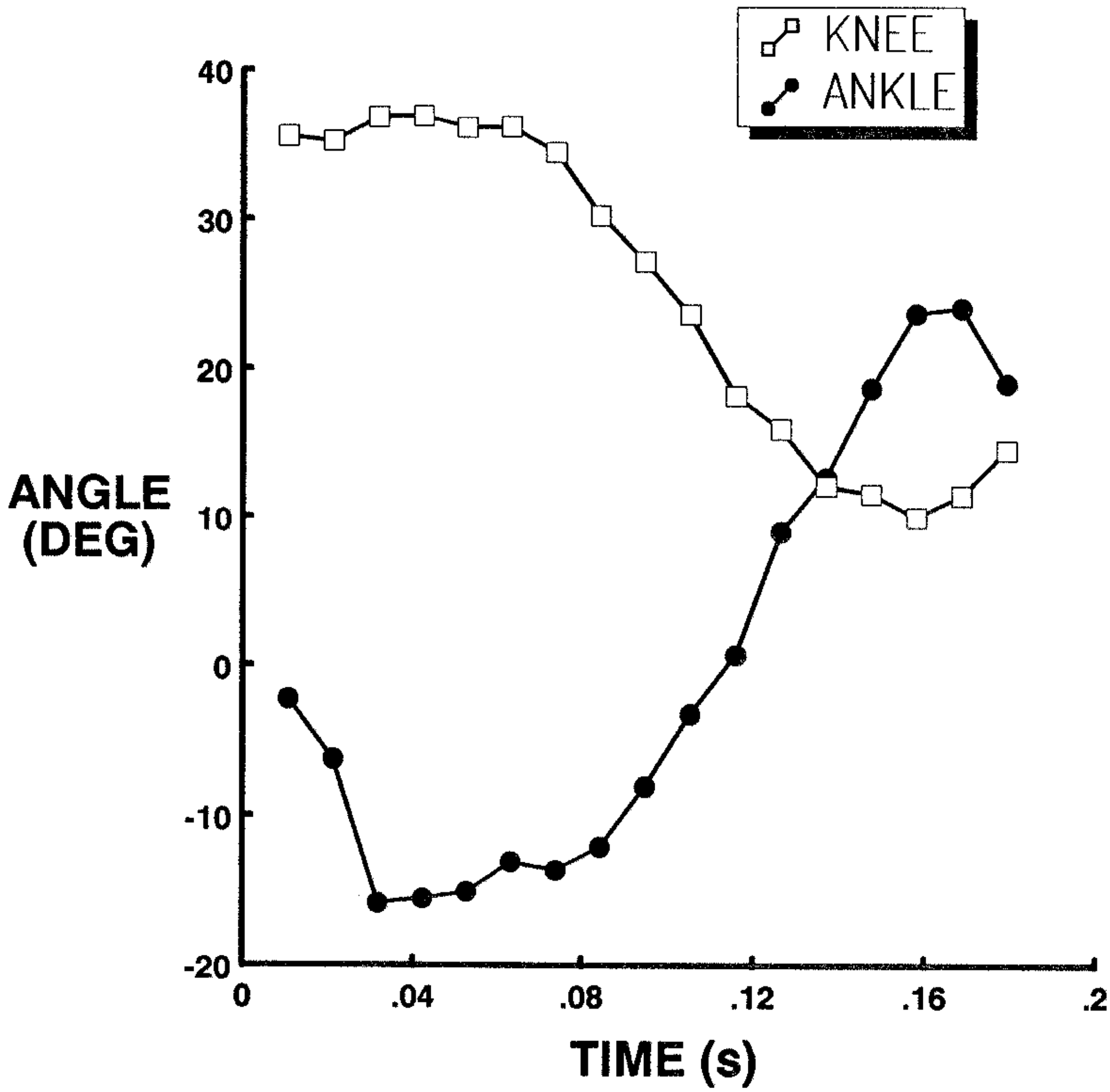

Fig. 37 Joint motions for Subject 8, Condition 2

skipping better than Subjects 3 and 7. The stresses upon the lower extremity were handled better across the articulations by Subjects 1 and 8.

Jogging Style

Subjects 9 and 10 were nearly identical across all variables. Subject 5 was similar in many aspects, but there were some important differences. As Figures 16a, 16b, and 38 demonstrate, the force-time curves were similar with long duration of F_z at peak. The directional forces, F_x and F_y, were more apparent in Subject 5, although F_x is also prominent in Subject 10. Subject 5 also had a slightly higher F_z than the other two subjects.

The directions and magnitudes of the ankle and knee moments were very similar for Subjects 9 and 10 (see Figures 39a, 39b). Subject 10 had a slightly higher and sharper peak knee moments that corresponded to a slightly higher and sharper peak F_z. As observed in Figure 40, Subject 5 showed a completely different pattern in magnitude and direction of the moments. Although the magnitudes of the ankle and knee moments were lower for Subject 5, the ankle and knee were not working together. The knee was taking the majority of the force at impact. This may be a function of the extra directional forces and the timing of the motions at the ankle and knee. The maximal values of knee flexion and dorsiflexion as well as the peak moments about the joints occurred during

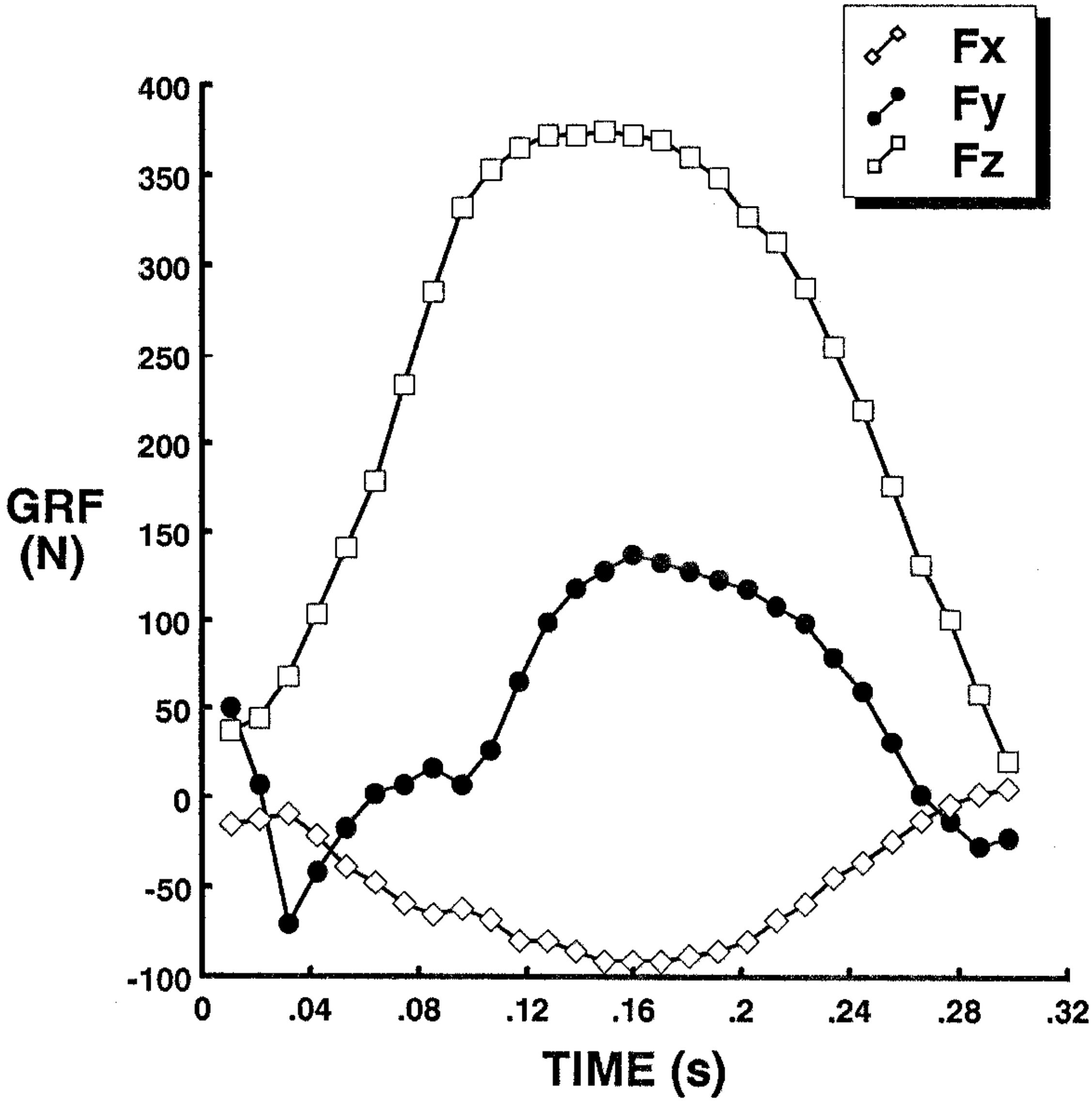

Fig. 38. Force-time curve for Subject 5, Condition 2

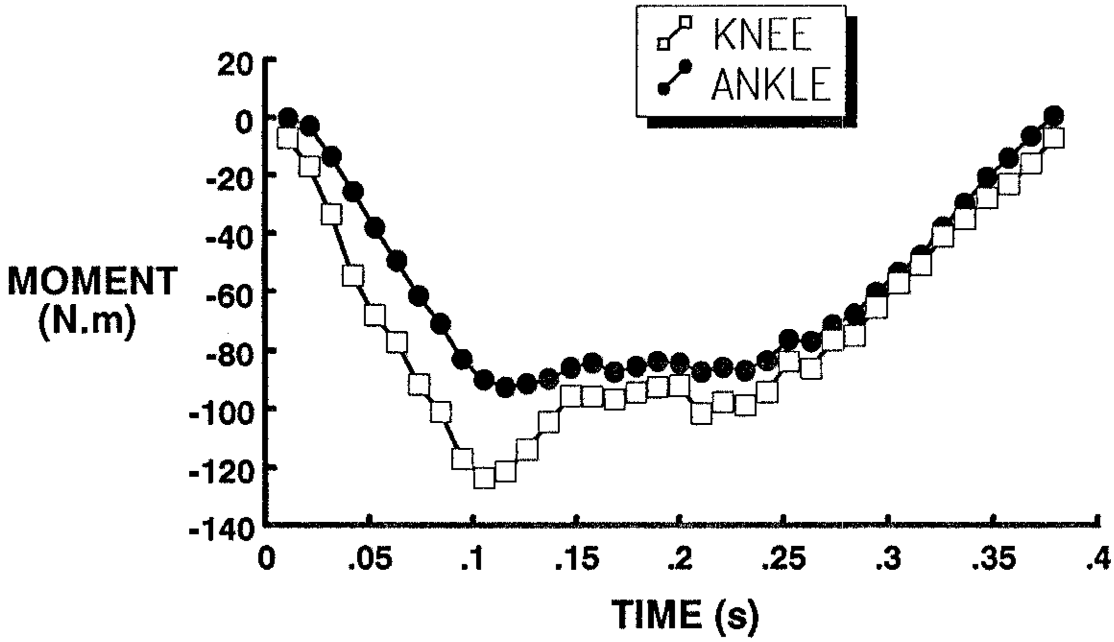

Fig. 39a. Moment-time curve for Subject 9, Condition 2

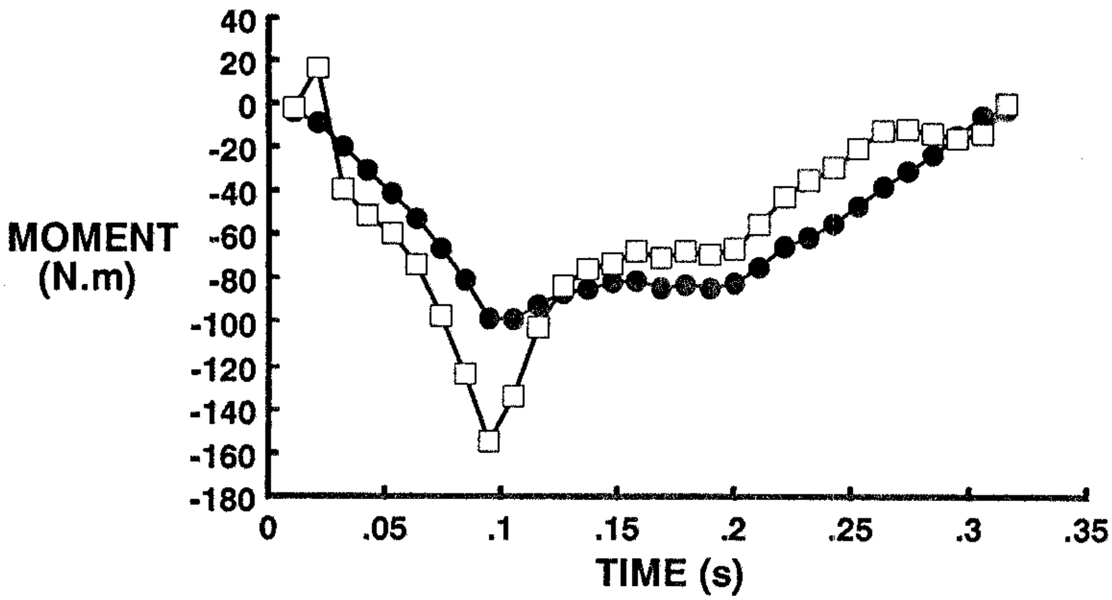

Fig. 39b. Moment-time curve for Subject 10, Condition 2

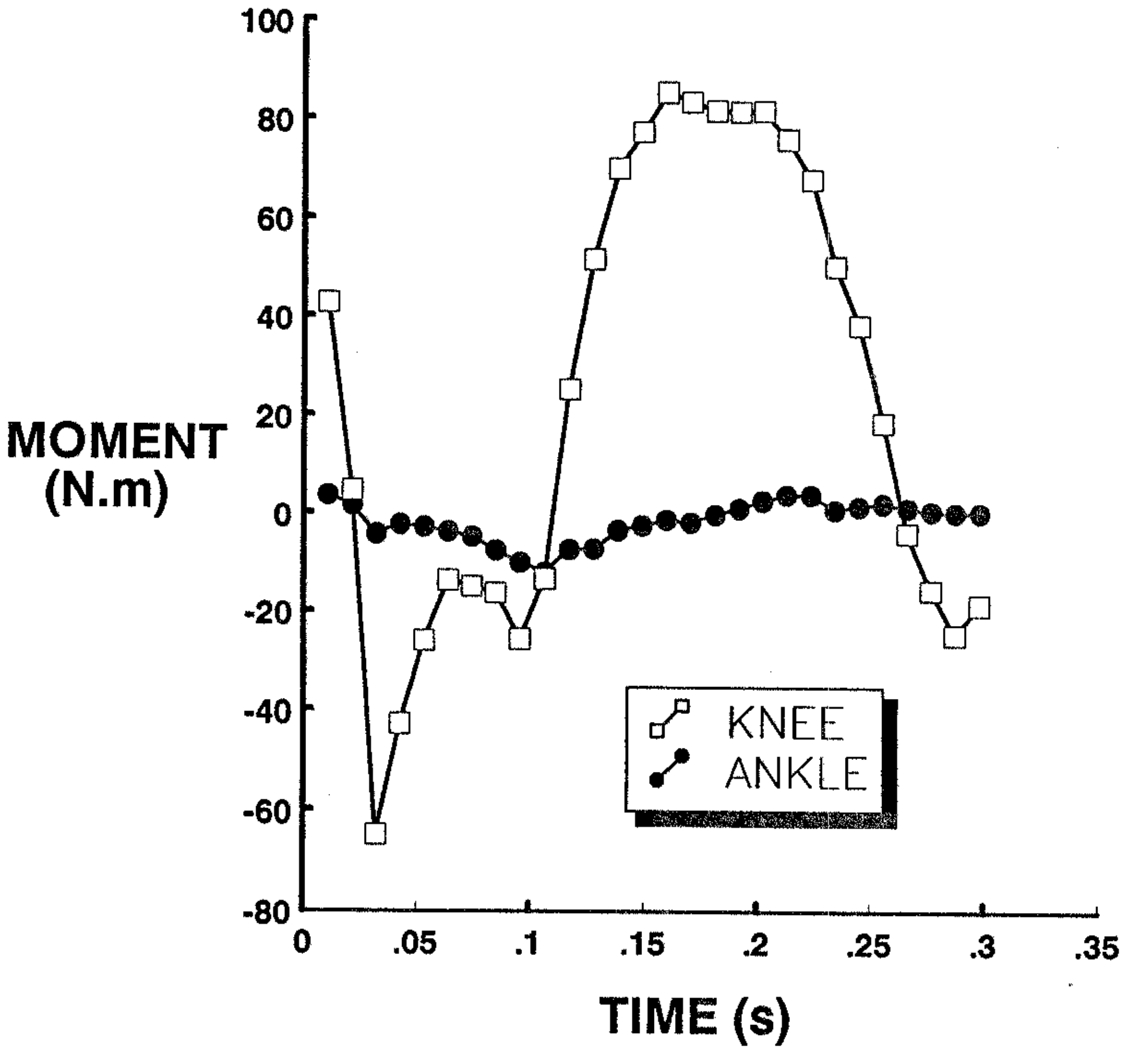

Fig. 40. Moment-time curve for Subject 5, Condition 2

the first half of the impact phase for Subjects 9 and 10. (See Figure 23.) Peak knee flexion and dorsiflexion occurred during the second half of the impact phase for Subject 5 as presented in Figure 41. The peak ankle and knee moments also occurred in the second half of the phase for Subject 5.

Rhythm Bounce

There was little similarity between the subjects across all variables. Subject 2 demonstrated the best results of this group. The force-time curve presented in Figure 17 shows a greater slope rising to peak with a lesser slope in the decline after peak. The ankle and knee moments were closely approximated in magnitude and direction, except at the beginning of the impact phase. (See Figure 42.) The knee presented an initial spike with little ankle activity. This may be as a result of a small initial spike in F_z and F_y that occurred before the knee had a chance to dampen the impact by flexing.

Subject 4 had a high peak F_z of 3.00419 BW with a short time-to-peak. Peak F_z occurred within a short span of high magnitude forces (see Figure 18). There was little impact reduction due to little knee flexion upon impact as observed in Figure 22. Knee flexion was just beginning as peak F_z was occurring. As a result of those stresses, there were high peak ankle and knee moments with the knee bearing most of the force of impact. The moment-time curves demonstrated the

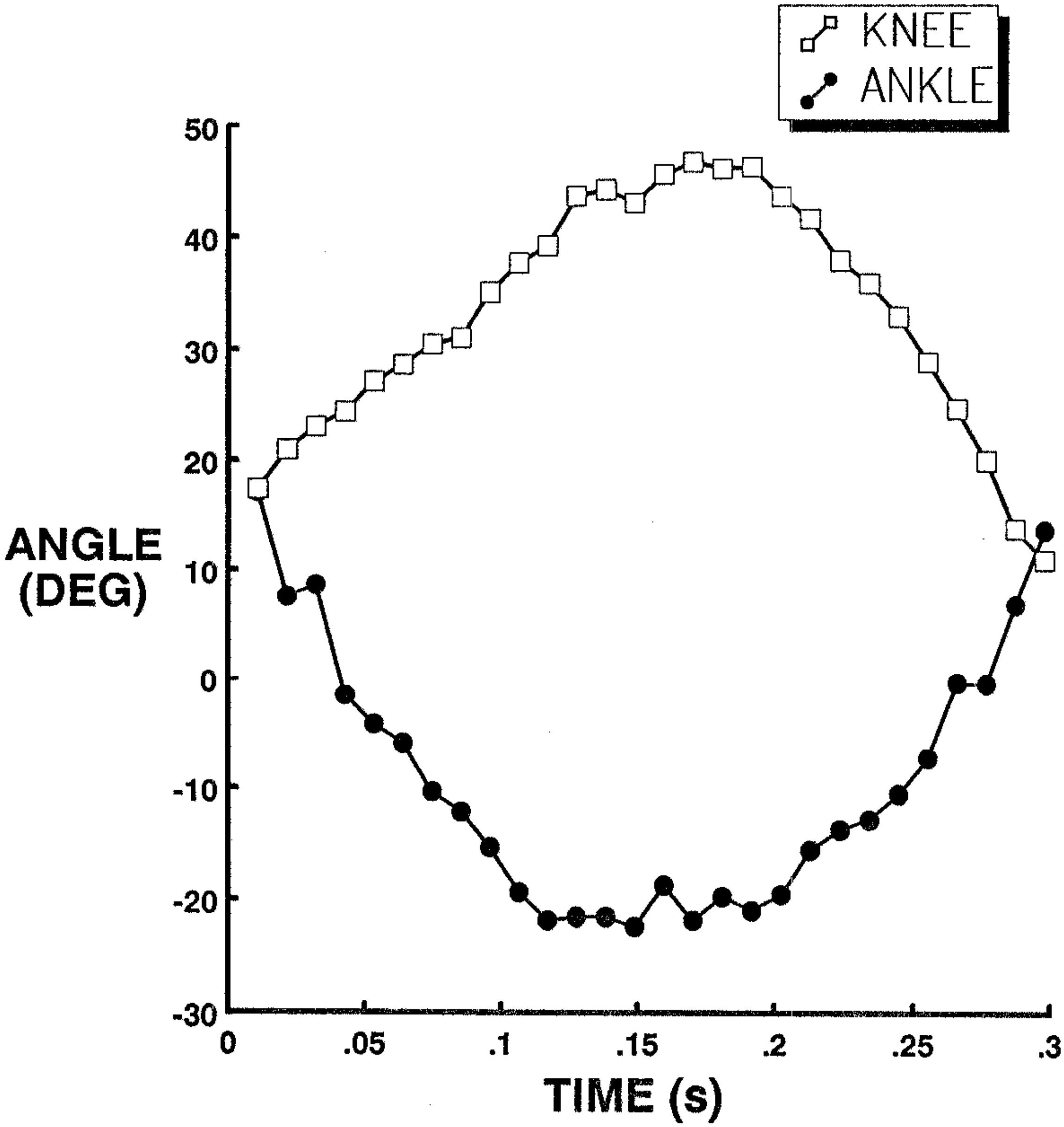

Fig. 41. Joint motions for Subject 5, Condition 2

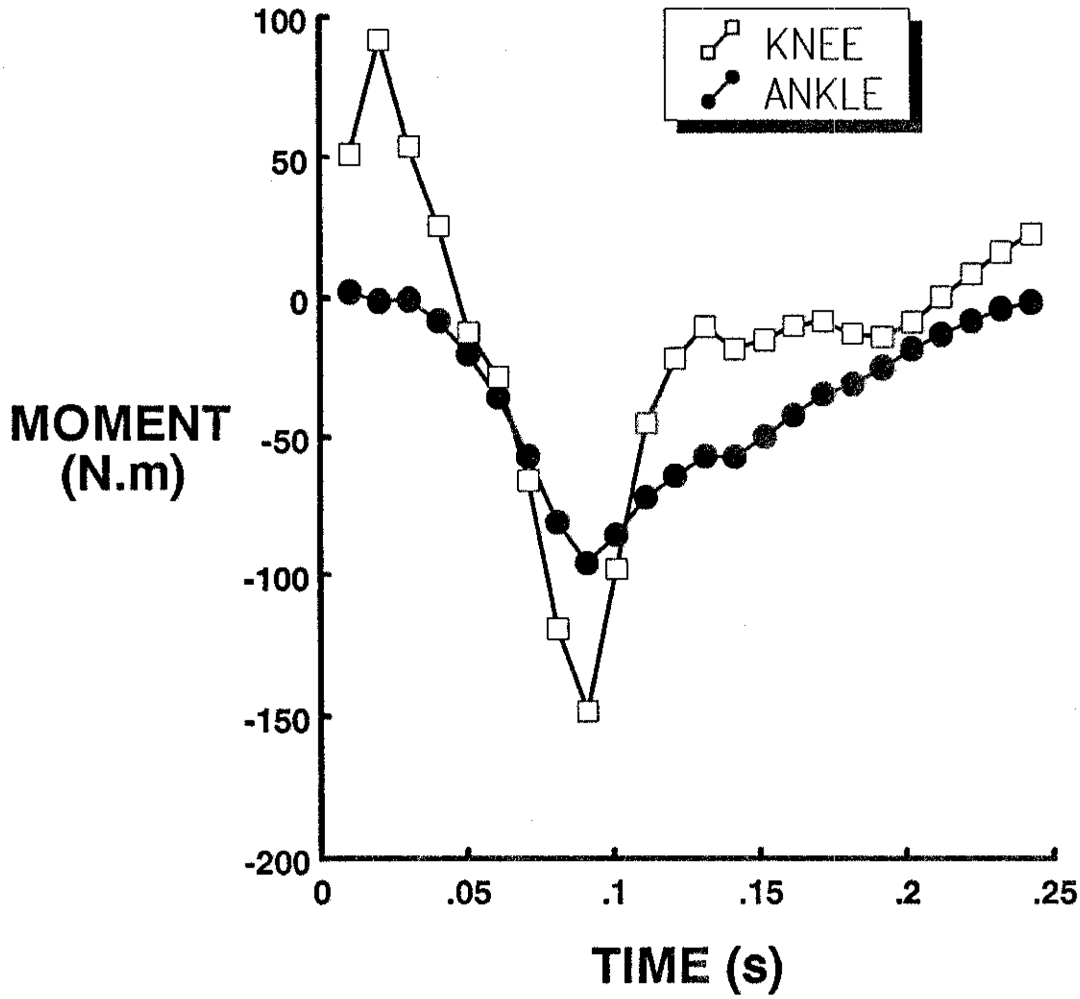

Fig. 42. Moment-time curve for Subject 2, Condition 2

disparity between the ankle and knee activity (see Figure 43a). The peak F_z and knee moments occurred approximately at the same time.

Although the peak F_z was the lowest for this style, Subject 6 presented a poorly phased impact. Figure 19 demonstrates considerable activity at the very beginning of the impact. There was a higher braking force than vertical force. The vertical force was itself high at the beginning of the impact, although it was not the peak F_z recorded. The peak knee moment occurred at the beginning of the phase and the ankle moments were small in magnitude with little variation in direction (see Figure 43b). Without time to enact dampening of the impact through ankle and knee flexion, the activity in the GRF and high knee moments indicated that this subject's knee underwent much abuse.

The secondary impacts were as variable as the primary. Subject 2 was the best at handling the impact across the articulations, while Subjects 4 and 6 demonstrated problems. Subject 4 showed variability in magnitude and direction. Again, Subject 6 had considerable activity at the beginning of the impact. Figures 44a - 46b are the force-time curves and moment-time curves for Subjects 2, 4, and 6 for the secondary impacts.

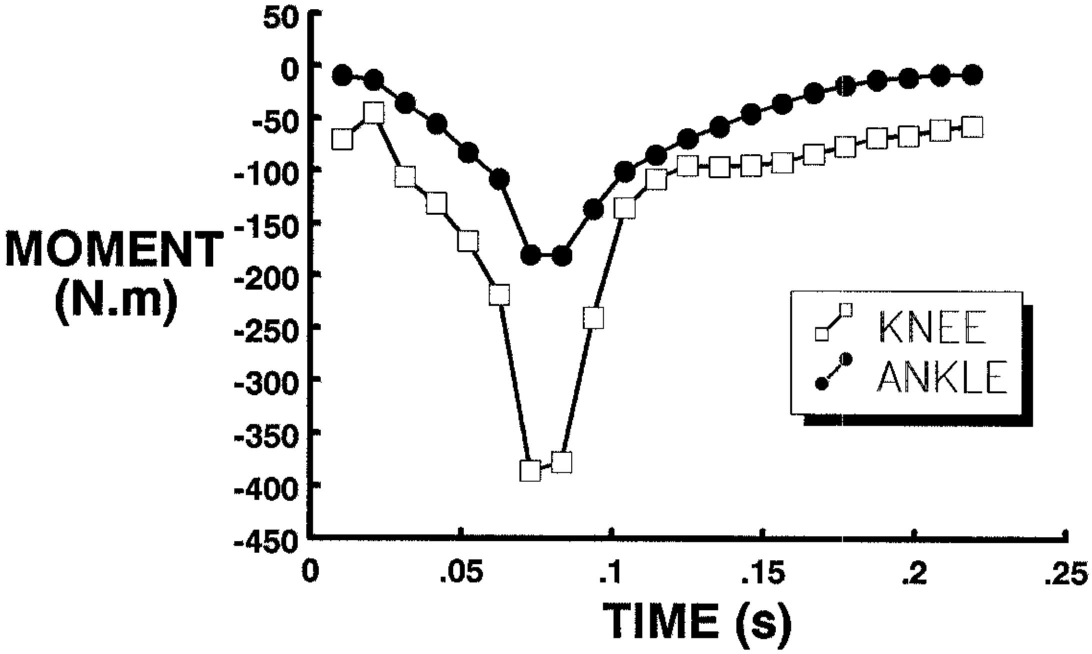

Fig. 43a. Moment-time curve for Subject 4, Condition 2

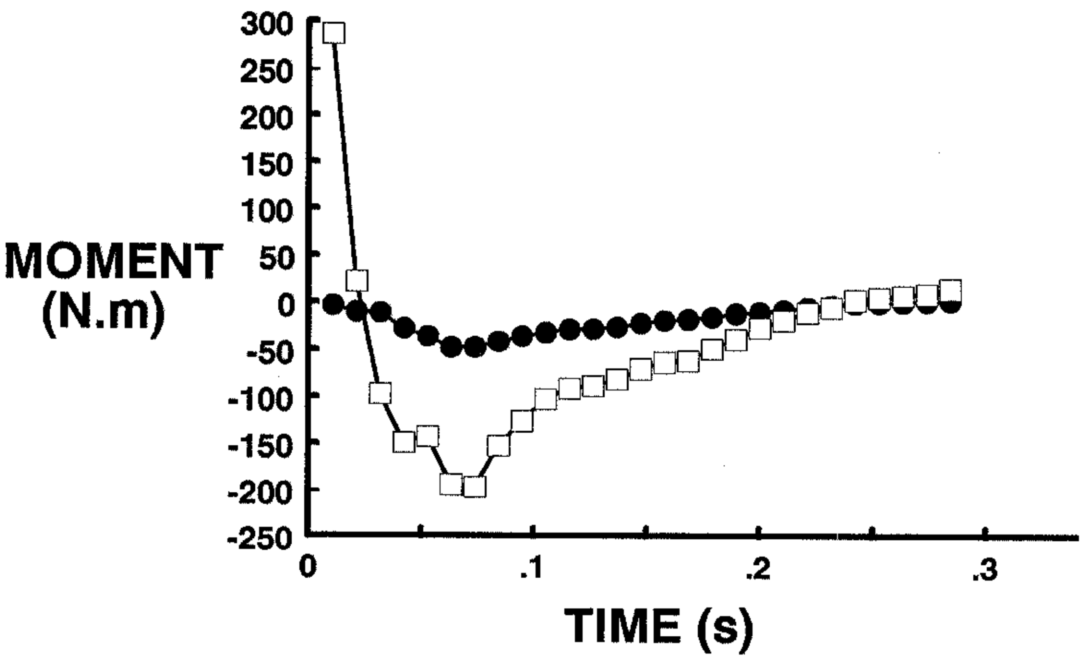

Fig. 43b. Moment-time curve for Subject 6, Condition 2

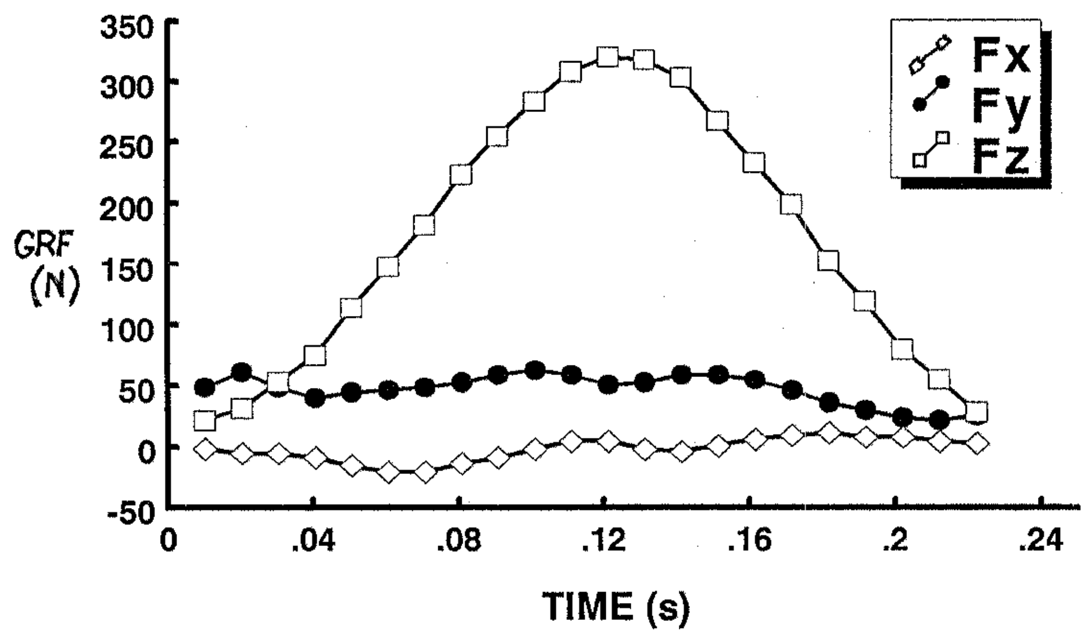

Fig. 44a. Force-time curve for Subject 2, Condition 2, Secondary impact

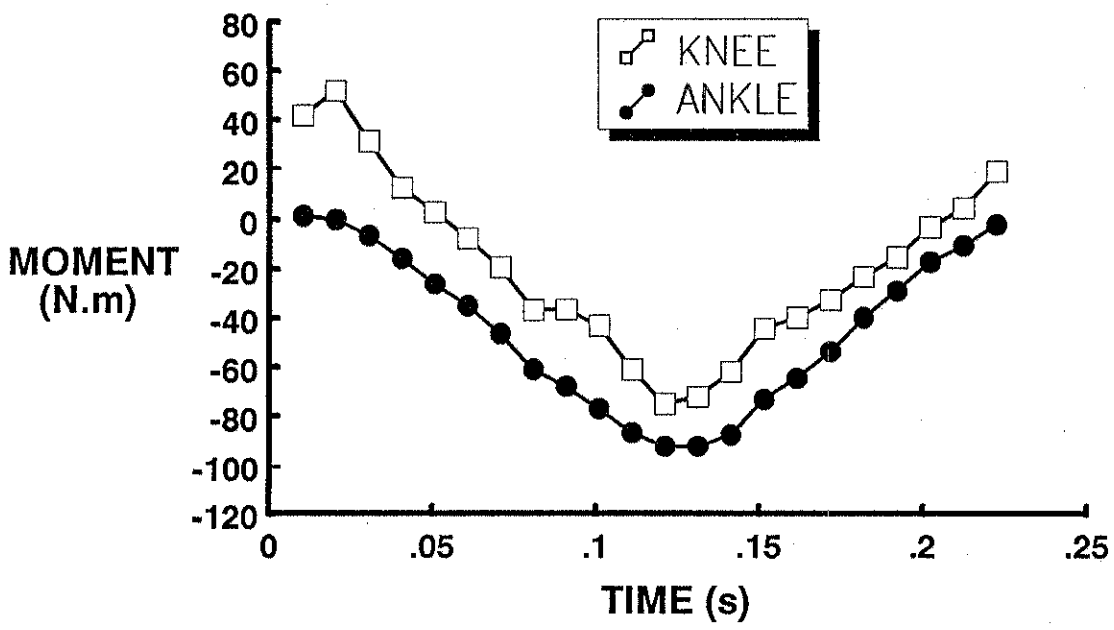

Fig. 44b. Moment-time curve for Subject 2, Condition 2, Secondary impact

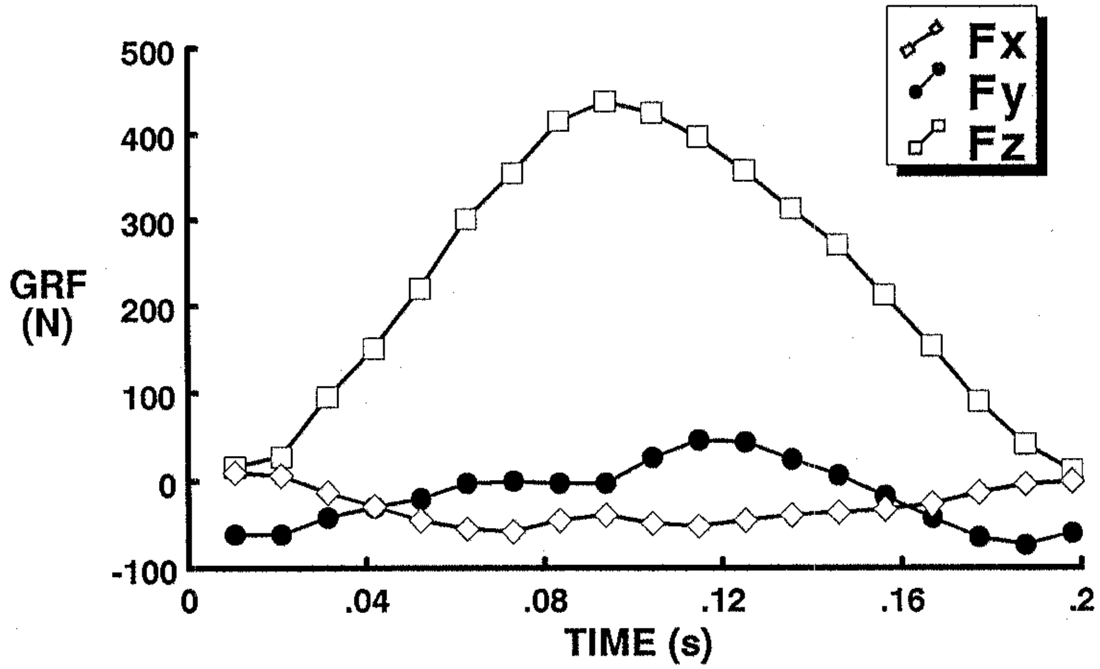

Fig. 45a. Force-time curve for Subject 4, Condition 2, Secondary impact

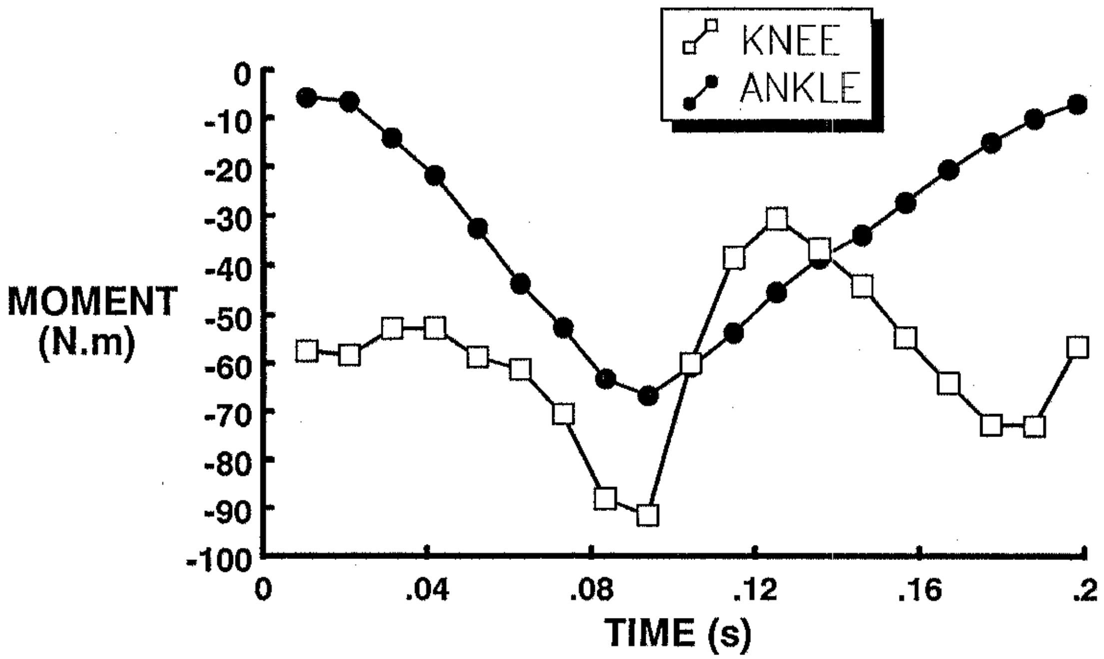

Fig. 45b. Moment-time curve for Subject 4, Condition 2, Secondary impact

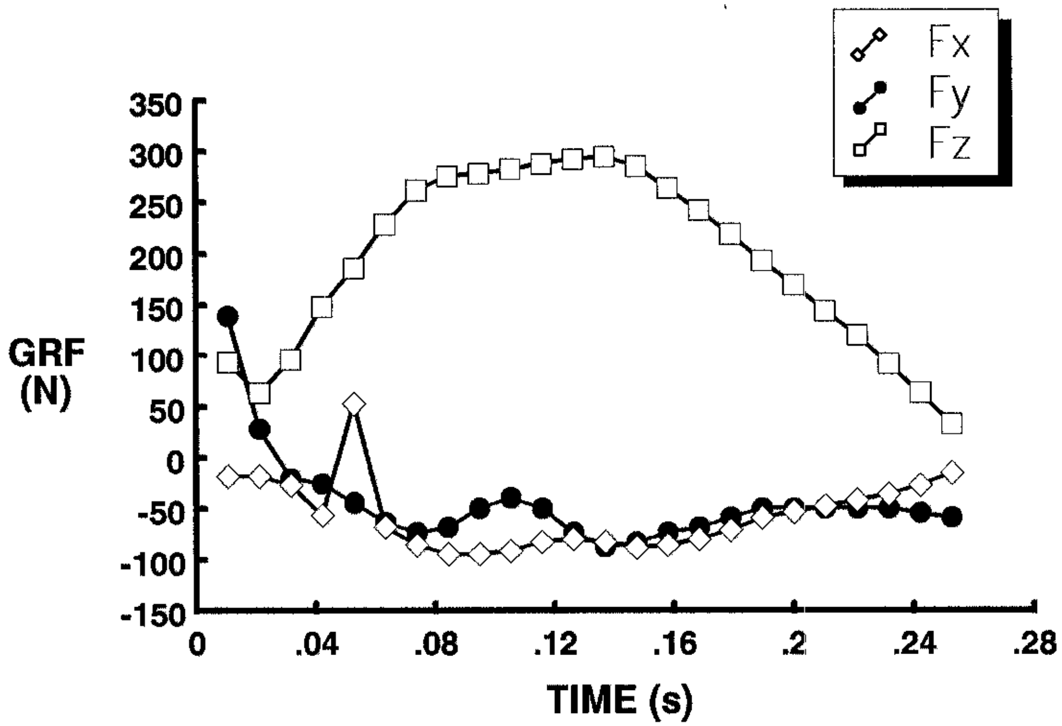

Fig. 46a. Force-time curve for Subject 6, Condition 2, Secondary impact

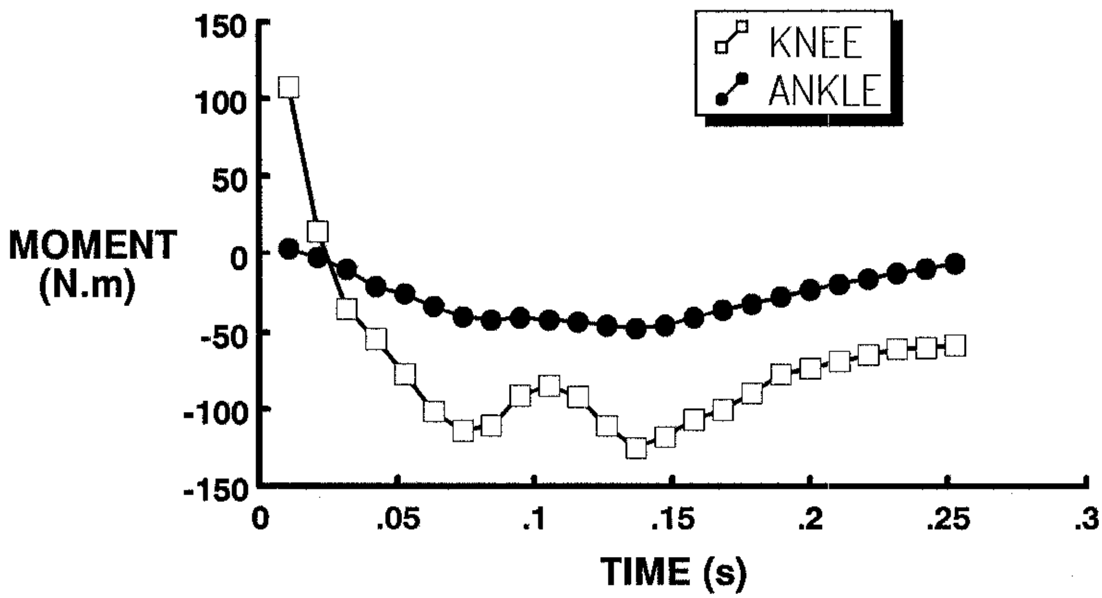

Fig. 46b. Moment-time curve for Subject 6, Condition 2, Secondary impact

Comparison Between Styles in Condition 2

The magnitudes and patterns of activities observed in the three styles were different, but the factors that influenced those values and patterns were the same. High peak vertical forces were associated with short times-to-peak. However, the high F_z might not be detrimental if it was distributed well across the articulations, determined by the joint moments and joint motions. Subject 8 had a high F_z but good patterns of joint motion and a good distribution between the ankle and knee moments. Subject 4 also had a high peak F_z, but did not distribute the forces as well as Subject 8 as determined by the lack of motion at the knee and variability in magnitude and direction of the ankle and knee moments. The same was observed for the lowest peak forces. Subjects 9 and 10 presented good impact absorption and distribution of stress, whereas Subject 6, with the lowest peak F_z, presented a poorly phased impact. The factors influencing the results may be dependent upon technique. Technique influences the ability to dissipate force. Technique also determines how those forces are dissipated. Two people can experience the same amount of impact over the same time frame but dissipate it very differently in their segmental movements. This may be a function of skill as well as technique.

Due to variability between and within the styles, as well as a low total number of subjects, one style cannot be recommended over another. The rhythm bounce is relatively easy to learn, but may not be the best style to use as technique and skill improve. The jogging style produced good results, but were not consistent across all subjects. The single bounce generally produced higher GRF with ankle and knee moment magnitudes between the jogging style and rhythm bounce style. The subjects utilizing the single bounce style displayed both good and poorly phased impacts.

Comparisons Between Conditions

The factors that influenced the results were once again more important than the styles themselves. Subject 2 was able to reproduce the patterns of movement and the time histories of force and joint moments across both conditions using the same style. The subject showed consistency in the magnitudes and sequencing of the variables. Subject 8 demonstrated well phased impacts over two different styles. Subjects 4 and 6 produced different values, force patterns, and moment patterns using the same style. Therefore, technique and skill may be more important than style. Skilled performers will be more consistent, efficient, and predictable in their performance. Although all subjects had used rope skipping as some form of exercise, Subjects 4 and 6 appeared the least skilled.

Conclusions

The criterion for determining the efficiency and nature of a well phased impact during rope skipping is not determined just by the peak vertical GRF and its time-to-peak. It is at least partially determined by a combination of (a) the GRF, (b) similarities in magnitude and direction of the joint moments, and (c) sequencing of the segmental movements.

Rope skipping is similar to jogging and other jumping techniques in the magnitudes of the peak vertical ground reaction force. Ankle and knee moments calculated in this study were less than the moments calculated in the drop jump studies reviewed.

The findings in this study suggest that the risk of injury while using rope skipping as an exercise is comparable to the risk associated with jogging and drop jumps. The impact variables, independently, are not of such magnitude that would directly cause an injury. However, the other factors that may lead to injury, such as overuse and poor technique, that are inherent in any weight bearing exercise, would need to be considered for rope skipping as well.

One style of rope skipping cannot be recommended over another style based upon this study. Technique and even distribution of force across the articulations appear to be more important than the magnitudes of the force produced by a given style. It is how the style is performed, not the style itself that appears to influence the impact variables.

Suggestions for Further Study

The investigation into the biomechanics of rope skipping could be further enhanced by:

1. using a larger sample;
2. controlling for height and weight of the subjects;
3. using a force plate that will produce usable readings at its edge to decrease possible adjustments in subjects' skipping styles in attempts to hit the target area on the force plate;
4. using two force plates, side-by-side to examine differences between the lower extremities;
5. not allowing the subjects to perform the same style for both conditions;
6. examining the influence of fatigue upon impact variables;
7. examining other variables such as velocity and acceleration of the segments and the entire body;
8. examining multiple impacts within a sampling for each condition.

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APPENDIX

INFORMED CONSENT

USE OF HUMAN SUBJECTS

INFORMED CONSENT

NAME OF SUBJECT:____

1. I hereby give consent to Susan A. Chinworth (Dr. A. Jackson) to perform or supervise the following investigational procedure :
   1) Record rope skipping performances using high-speed cinematographical techniques;
   2) Take direct measurements of reaction forces experienced underneath one foot using a force plate.

2. I have (seen,heard) a clear explanation and understand the nature and purpose of the procedure;possible appropriate alternative procedures that would be advantageous to me; and the attendant discomfort or risks involved. I have (seen,heard) a clear explanation and understand the benefits to be expected. I understand that the procedure to be performed is investigational and that I may withdraw my consent for my status. With my understanding of this, having received this information and satisfactory answers to the questions I have asked, I voluntarily consent to the procedure designated in Paragraph 1 above.

SIGNED:____________________ SIGNED:____________________
Witness Subject
or

SIGNED:____________________ SIGNED:____________________
Witness Person Responsible

____
Relationship

Instructions to persons authorized to sign:
If the subject is not competent, the person responsible shall be the legally appointed guardian or legally authorized representative. If the subject is a minor under 18 years of age, the person responsible is the mother or father or legally appointed guardian. If the subject is unable to write (his,her) name, the following is legally acceptable:John (his,her X Mark) doe and two (2) witnesses.

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