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D. Paul Roche
University of Windsor

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A CINEMATOGRAPHICAL ANALYSIS OF SKILLED RUNNERS DURING THE CONTACT PHASE

A Thesis
Submitted to the Faculty of Graduate Studies through
the Faculty of Physical and Health Education
in Partial Fulfillment of the Requirements
for the Degree of Master of Physical
Education at the University
of Windsor

by

D. PAUL ROCHE
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Faculty of Graduate Studies

Faculty of Physical and Health Education

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Physical Education

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Sept 16/71 ____________ Thesis Chairman

Sept 16/71 W. North ____________ Committee Member

Sept 16/71 ____________ Committee Member

ABSTRACT

In this study, 8 male track athletes were filmed at 308 pictures per second while running at 3 velocities. Focus of study was placed on the relationship of the point of contact of the leading foot to the center of gravity of the body. The other factors examined were: angle of upper body lean; angle of the upper leg; the angle of the lower leg; and the position of the foot at contact.

A computer program was designed to calculate the horizontal distance from the point of contact to the center of gravity and to compute body segmental angles. An ancillary program plotted stick figures for each frame analyzed and grouped selected frames to illustrate the sequential pattern of body movement during contact.

The results of this investigation indicated that with a decrease in running velocity, foot contact was made more closely under the center of gravity. It was also found that the angle of upper body lean increased with an increase in velocity during middle and later stages of contact, but this lean varied among runners and deviated only slightly from the perpendicular. In the early stages of contact, the angle of the upper leg became more horizontal at maximum than at the slowest velocity. The range of the angle of the lower leg at touchdown was found to be from 74 to 91 degrees. Foot contact did not necessarily become more flat-footed with a decrease in velocity.

It was also shown that the dorsiflexion of the ankle is extremely important in cushioning the impact of the body at initial contact, particularly during heel and flat-footed running. It was also found that movement of the hip joint is minimal in the frontal plane during contact.

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CHAPTER I

INTRODUCTION

Although running is a main method of locomotion used by man, relatively little has been written about it in terms of the mechanical analysis of the movement. A possible reason for this is that there seems to be as many assumed correct styles of running as there are runners, and these styles vary, supposedly, from the high-kneed power stride of the sprinter to the shuffling gait of the marathoner.

It would appear that the differences attributed to various running styles for different runners depend, to a great extent, on judgements made solely with the naked eye and on coaches who feel that they are authorities because of past experience and observation. This, then, may raise the question as to whether these differences really do exist, and if so, to what extent? For example, is the sprinter's foot placed in a different position in relation to the rest of his body, than is the foot of the long distance runner? To the naked eye it would seem that the positions are quite different, but high speed photography indicates that this difference might be exaggerated.

THE PROBLEM

The purpose of this study was to determine if variation in running velocity altered foot placement, the angle of body lean, the angle of the upper leg, the angle of touchdown and the position of the foot during the contact phase. More specifically, measurements were made to find: (1) the horizontal distance from the point of foot contact to a line drawn vertically to a point representing the center of gravity of the body, (2) the angle of the leading upper leg, (3) the angle of the leading lower leg, (4) the angle of the leading foot, and (5) the angle of the upper body lean. These measures were found for three different velocities at three stages of contact.

Importance of the Study

At present the lack of quantitative information on the relation of the center of gravity of the body to foot placement hinders complete understanding of the mechanics of running and inhibits the isolation of those factors which may vary relative to the distance and velocity which a runner must run. Knowing the relationship of the location of the representative center of gravity of the body to the contact surface for varying velocities may help coaching by substantiating presently recommended track techniques or by suggesting new ones. Although some authors have indicated that the point of contact is slightly ahead of the center of gravity of the runner and that this distance decreases with an increase in speed, scientific evidence is lacking to support these claims.

An intricate examination of the contact phase would seem vital in discriminating the effect that velocity has on the orientation of various body segments during running. It is important that the relationship of these body segments in skilled runners is known so that means to best running efficiency may be discovered. Careful study of the angle of body lean and the angles of the lower limb segments may clarify proper running technique.

Purpose of the Study

The purpose of this study was to isolate the effect of velocity on the contact phase in running. By using high speed photography and by controlling velocity, it was hoped that a broader unerstanding of the biomechanical differences in running at different velocities could be achieved. By determining the extent of morphological commonality among velocities it was also intended that the value of coaching might be ascertained.

Delimitations

Eight male track athletes attending the University of Windsor were filmed using high speed photography. Filming was done at right angles to the plane of motion with optimal lighting conditions on a single day. Data were extracted from examination of the contact period of the left leading limb during running trials in which velocity was controlled. Analysis was facilitated by means of computer programming.

DEFINITION OF TERMS

The following definitions are provided to permit an understanding of the terms as applied to this study:

Representative Center of Gravity. As filming was done in the sagittal plane, the left greater trochanter served as the anatomical landmark to represent the center of gravity of each runner.

Leading Lower Limb. The left leg just prior to and during contact was selected as the leading lower limb as it was closer to the camera.

Contact. Contact was defined as the phase during which the leading foot touched the ground. In this study, contact was delineated further into initial contact, effective contact and center of gravity contact.

Initial Contact. The instant at which contact was made with the ground was called initial contact.

Effective Contact. Effective contact was defined as contact in which the lower leg reached an angle of 90 degrees to the running surface.

Center of Gravity Contact. Center of gravity contact was contact in which the hip joint was directly over the point of contact.

ORGANIZATION OF THE REMAINDER OF THESIS

The remainder of this thesis is divided into five chapters. The second chapter examines the literature related to this study. Chapter three contains the procedures used to conduct the investigation. In chapter four are the results of this study and the following chapter consists of a discussion of these results. The summary and conclusions are listed in chapter six.

CHAPTER II

REVIEW OF LITERATURE

An investigation into the effect of velocity on running during the contact phase was examined in this study.

This chapter contains a review of literature pertaining to the mechanics of running and particularly to those sources related to the contact phase and running velocity, the central problem of this study. While numerous coaching articles have dealt with training methods involved in running, few quantitative studies have been conducted on body mechanics of any phase of running, and fewer still have examined the contact phase.

Earliest records on running analysis were reported prior to the twentieth century, but these studies lacked precision due to the inadequacies of the equipment. The crude force platform used by Amar (16) was typical of the mechanical devices used in running analysis at the turn of the century. Although photography was used to some degree, it was limited to sequential still photography in applications similar to the investigation by Muybridge (10) into numerous forms of locomotion.

The development of moving pictures provided a new tool for motion analysis which has been refined to the current extremely sophisticated techniques involving high speed photography with computer analysis.

The earliest studies using cinematography are those by Fenn (27) who developed the initial quantitative film analysis techniques. His photography involved the use of a hand-cranked camera capable of 120 frames per second. As film speed was irregular, frame rate was calculated by dropping croquet balls in front of a vertical scale within the photographic view. A coordinate system was also established by placing a white lattice-work construction of one-meter squares between the camera and the runner. The methods adopted by Fenn provided the foundation for several studies which followed.

Various investigations have been reviewed in this chapter. For best examination of the research on the mechanics of running, the literature may be divided into the following headings: (1) body inclination, (2) stride length, (3) foot placement, and (4) center of gravity.

BODY INCLINATION

Several investigators have studied body inclination in running and have indicated its importance. There is, however, some disagreement on the most desirable body lean. Morehouse and Cooper (8) stated that the body leans forward during running in order that the center of weight of the body is placed ahead of the driving action of the legs. Even though they admitted that some successful runners appear to run erect or even with a slightly backward lean, leaning forward over the the contact foot was recommended. Rasch and Burke (11) and Soule (42) supported the concept of forward lean while Jensen and Shultz (7) went further by stating that occasionally a runner had to be taught to lean forward. Bunn (2) also recognized the forward lean and suggested that it helped to overcome air resistance.

In opposition to this view is the observation by Slocum and James (41) that the position of the trunk was essentially erect and that forward lean shifted the center of gravity, upsetting forward balance. They proposed that forward lean may be a product of faulty coaching.

Dyson (6) supported this view and might have answered the controversy by suggesting that there may be an illusion of forward lean by observing a runner when his driving leg is fully extended. An alternate solution to the problem is suggested by Wilt (43) and Chapman (21) who indicated that the forward lean is directly related to acceleration. As top speed approaches, acceleration and body lean decrease.

Effect of Velocity on Body Inclination

There seems to be a common feeling that as an athlete runs faster, the body inclination becomes greater. Morehouse and Cooper stated that, ". . . The extent of the lean is in proportion to the rate of running. A sprinter running maximum speed will lean forward about 25 degrees from the vertical. Distance runners, applying less driving force will lean forward only about 15 degrees. . . ." (8:242) Rasch and Burke (11) in agreement, suggested a forward lean of 20 to 25 degrees during a sprinter's maximum speed. Jensen and Shultz (7), Broer (1) and Scott (12) all observed a progressive incline of the upper body as speed increased.

Four grade school girls were studied by Dittmer (48) over a 5-year period to analyze the development of the running pattern and to isolate factors which distinguish good from poor performers. At contact, the better performers were found to be running with increased forward lean. Trunk inclination was measured from the middle of the trochanter to a position midway between the shoulders.

Osterhoudt (50) examined skilled runners at controlled submaximum velocities to observe the effect of speed and slope on selected biomechanical factors. The mean body angle at contact was found to decrease with a decrease in speed.

In summary, it seems that most of the authorities felt that the body does incline forward in running and that this inclination increases with increased velocity.

STRIDE LENGTH

Stride length is another area of controversy in the literature. Some authors felt that running efficiency can be improved by increasing the length of the stride. Deshon and Nelson (22) for example, stated that a long running stride was a factor in efficient running. Hogberg (31) however, examining the influence of stride rate and stride frequency on oxygen consumption found that the most economical stride length was closest to that freely chosen by the subject. In this study, Hogberg used the treadmill and examined only one subject.

Effect of Velocity on Stride Length

There is general agreement that stride length increases accompany speed increases.

In one of the earliest experimental analyses utilizing a treadmill, Hubbard (33) evaluated the differences between 5 trained and 5 untrained male runners. Kymographic records of muscular activity were taken from trials of walking and running at a pace selected by the subjects themselves. No evidence was presented indicating whether anatomical differences existed between the trained and the untrained runners, however Hubbard found stride length was 16 percent higher among trained than untrained runners. He concluded that improvement in running resulted from increasing stride length rather than the rate of striding.

In a cinematographical analysis of sprinting Deshon and Nelson (22) used 19 male varsity athletes to examine the relationship between running velocity and stride length, the angle of touchdown, and the angle of leg lift. Statistically significant intercorrelations were found to exist between all variables except mean angle of leg lift and mean angle of touchdown. It was suggested that the results tended to support the concept that efficient running was characterized by a high knee lift, long running stride and placement of the foot as closely as possible beneath the center of gravity of the runner. Only maximum velocity of each subject was evaluated.

More recently, Teeple (52) conducted an investigation into the effects of speed changes on selected biomechanical factors for 28 college women classified as either slow or fast runners. Her subjects were filmed at 120.5 frames per second as they ran at maximum speed and at two submaximum speeds with the assistance of a speed-pacer set at 11.5 and 16.0 feet per second. Data were extracted directly from the film using a Vanguard Motion Analyzer so that the coordinates of segmental end points could be fed into a computer program to determine segemental angles and the location of the center of gravity by means of the segmental method. The center of gravity was calculated solely during take-off.

In her study, changes in running speed resulted in significant differences in velocity, stride rate, stride length, time of support, time of non-support and angle of leg lift. Angle of touchdown for submaximum speeds and the angles of trunk lean and take-off yielded no significant differences. She concluded that the primary biomechanical factor associated with running ability was time of support, and that stride rate, stride length, angle of leg lift and time of support are significantly altered by changes in speed.

Osterhoudt (50) found increases in both stride rate and stride length with an increase in the submaximum velocities examined and also in the three slopes used.

Some discrepancy to these views was presented by Hogberg (30). He refuted these findings in part when he indicated that at higher speeds, optimum for each runner, speed was increased mainly by increasing stride frequency. His results at lower speeds, however, were in agreement with other investigations. This treadmill study of well-trained runners may be limited in that only 2 subjects were used.

Hogberg indicated that an effort to increase stride length by stretching the lower leg forward was uneconomical because:

> . . . the center of gravity of the body takes longer to come into such position that it lies in front of the forward foot. Good runners set the foot a very short distance in front of the vertical line running through the body's center of gravity . . . . (31:139)

Rapp (51) attempted to determine the effect of velocity on stride length and body-rise of 18 skilled cross-country and track athletes. In changing from a slow to moderate pace, runners were found to increase stride length and decrease body-rise. While these findings are similar to those reported by Hogberg (30), it should be noted that Rapp did not adequately control the running velocity of each trial. The two-mile, 880 yard and maximum effort paces were regulated solely by verbal instruction. Although frame rate was reported as 64 frames per second, no evidence was given for film speed validation. The study may further be limited in that subjects altered their normal running stride in order to trigger switch mats.

In summary, although there is some disagreement on the effect of velocity on stride length it is generally accepted that progressive increases in stride length are associated with faster running.

FOOT PLACEMENT

Discussion of foot placement has been studied mainly in relation to the position of the foot at contact, in relation to the center of gravity of the body, and in relation to different velocities.

Position of the Foot at Contact

It is generally accepted that the sprinter contacts the ground on the outer ball of the foot. Slocum and James (41) examined the shoes of fifty unselected track men and found greatest wear on the outer side of the sole in the metatarsal weight-bearing area. Toni Nett (35) investigating foot contact in varying running events with a camera situated 20 to 30 centimeters off the ground and operated at 64 frames per second, observed that runners of international caliber at all distances first contacted the ground on the outside edge of the foot.

In his study, Osterhoudt (50) noticed that regardless of speed or slope, the heel inevitably contacted the ground during support and that initial contact always occurred on the lateral border of the foot. It is important to note, however, that the observations of both Nett (35) and Osterhoudt (50) were made in the sagittal plane. It would seem that confirmation of the lateral position of the foot at contact must await study in the frontal plane.

Fenn (27) instructed physical education students to run at top speed as they passed in front of a camera. His subjects landed flat-footed or lightly on the heel even at top speed. It should be noted, however, that running speed was neither measured nor controlled.

Although Hubbard's (33) comments on foot placement were not based on measurements, he observed that the contact foot, which served as support from which ballistic movements could be thrown, can be effective in either a flat or extended position. He then concluded that distance runners should light on the heel with the gastocnemious relaxed.

Nett's (35) observations also lacked quantification, however he noticed that the position of the foot became increasingly flat with an increase in running distance. After reviewing kinesiology literature Dittmer (48) stated that in ordinary running and with increasing speed, first contact should be made on the ball of the foot. Dittmer stressed that landing on the ball seemed to be advantageous in lengthening the stride. It is almost unanimously accepted by writers of kinesiology that distance runners contact the ground with either heel or flat-foot placement. Osterhoudt (50) drew similar conclusions from a review of track and field coaches. From his own study, Osterhoudt concluded that foot contact became increasingly more distal as the speed of run increased.

Foot Placement and Center of Gravity

Fenn (28) determined the horizontal and vertical movements of the center of gravity in running. The center of gravity was considered to be 10 centimeters above the hip joint. He found that with only slight exception, the rise of the center of gravity reached a maximum when the toe left the ground, and that the center of gravity fell between contacts. The point of contact was found to be ahead of the center of gravity for approximately 0.03 seconds.

The swinging limb in running was examined by Fortney (49) who used 8 boys aged 7 through 11 as subjects. Fortney explained that prior to contact, the landing foot is moving backward in relation to a fixed point in space and further that the heel is moving backward in relation to the knee. She suggested that the backward motion of the heel was advantageous in placing the leading foot more directly under the center of gravity of the body at the beginning of the contact phase and also in exerting force in the desired direction during contact. No attempt was made to locate the center of gravity or clarify the relationship between the body's weight center and the point of contact.

Clouse (47) in a kinematic analysis of running pattern development of preschool boys, filmed at 32 frames per second, followed the path of an estimated center of gravity of the body in space and determined the location of the center of gravity in relation to the contacting foot. A straight line drawn from the estimated center of gravity to the metatarsal phalangeal joint of the contact foot was termed the angle of inclination of the body. An angle of greater than 90 degrees indicated that the supporting foot was ahead of the estimated center of gravity, while angles less than 90 degrees placed the center of gravity ahead of support. Although the angle of body inclination decreased with skill, it remained greater than 100 degrees in all subjects. Clouse recognized that the center of gravity trailed contact, however she did not indicate the horizontal distance between these two points.

Bunn (2), in contrast to the findings of Fenn (28), Fortney (49) and Clouse (47), proposed that ideally the center of gravity should be kept in front of the striding foot at contact by leaning forward. He further indicated that the athlete who first contacts the ground with his heel, causes his center of gravity to fall behind the contact foot, thus creating a retarding effect equal to the body mass times the distance from contact to the center of gravity.

Effect of Velocity on Center of Gravity

Osterhoudt (50) examined the relationship of the heel to the hip during contact. His results, showing a decrease in horizontal distance from heel to hip when runners decreased velocity from 21 to 16 and 11 feet per second, question the assumption made by Dyson (6) that the distance in which the foot lands in front of the center of gravity of the runner decreases with an increase in velocity. Osterhoudt's data, however, may be limited in that the velocities examined do not permit comparison to sprinters and that selection of the heel as the point of contact may automatically infer that he compared different stages of contact among runners.

THE CENTER OF GRAVITY

Discussion of running mechanics often relates to the position of the center of gravity of the body as the center of mass and as the point of application of the resultant force of gravity acting on each segment. Cooper and Glassow stated, ". . . Within every mass there is a point about which the gravitational forces on one side will equal those on the other side. This balance point, determined in three planes of the mass is the center of gravity." (3:151) It would appear that many kinesiologists and coaches refer to the center of gravity as though it were an obvious position immediately recognizable to the casual observer. The location of this weight center, however, seems to vary slightly from individual to individual, between sexes, and with age. As the position of the center of gravity also changes with movement of body segments, there is difficulty in precisely determining this location in runners. Although the center of gravity of the body is a hypothetical construct, man attempted to locate this position accurately using mathematical precision as early as the seventeenth century (3:151).

Center of Gravity in the Erect Position

When the human body is in the erect position the center of gravity in the transverse plane can be calculated using the scale method developed by Reynolds and Lovett (39) in which a subject lies on a board supported at either end by knife-edges resting on weigh scales. The transverse plane has also been calculated to be approximately 55 percent of the individual's standing height measured from the soles of the feet. For example Braune and Fisher (18), using frozen cadavers, found a percentage of 54.8 of the height of the body.

The method of finding the center of gravity developed by Palmer (36) utilized the principle of moments of force around a fixed point on subjects lying in the supine position. From data on almost 1200 male and female subjects aged from birth to 20 years, he found that the transverse plane of the center of gravity can be estimated according to the formula:

$$y = 0.557\,x + 1.4 \text{ cm.}$$

In this formula, 'y' equals the distance of the center of gravity from the soles of the feet and 'x' equals stature. In the adult, the center of gravity was found to be positioned just over the brim of the pelvis and fairly close to the ventral border of the vertebral column.

Palmer indicated that nearly all investigators had located the center of gravity with reference to the transverse or frontal planes assuming that the mid-sagittal plane of the body passes through the weight center. As the human body is not perfectly symmetrical, he concluded that it was not feasible to attempt to locate the center of gravity in the sagittal plane.

Center of Gravity in the Moving Body

Locating the center of gravity in the moving body is a difficult task. Cooper and Glassow (3) indicated that the use of scales when the body parts are moving becomes impossible as pressure on the scales is affected by the force of the movements as well as the weight of the body parts. They suggested, however, that scales may be used by simulating body positions taken from photographs of the body in motion.

At present the segmental method proposed by Dawson (4) is generally the most accepted method for finding the center of gravity of the moving body. In order to use this method it is necessary to find the relation of the centers of gravity of all body segments to each other with reference to a vertical and horizontal axis drawn arbitrarily through the body. The segmental method also demands knowledge of the percentage weights of the body segments and does not permit the absence of some segments. Drillis (23) reviewed the numerous studies which investigated the percentage weights of body segments. Although minor differences existed among methods, generally, similar results were found using a variety of techniques, which included sawing frozen cadavers at the segmental end points and immersion of segments to determine volume displacement.

Using 16 millimeter film, exposed at 64 frames per second, Beck (46) determined the path of the center of gravity of boys from grades 1 to 6 performing a 30 yard run. By painstakingly tracing each frame she calculated segmental angles and the location of the body's center of gravity.

After reviewing various techniques available to find the weight center in the moving body, Beck selected the segmental method. As all segments must be visible in order to use this method accurately, it was necessary to assign values to the left upper limb which became hidden from view by the trunk during the contact phase. Prior to her study, Beck reasoned that a method of locating the center of gravity could be selected on the basis that the path of the center of gravity in space should display projectile-like characteristics and equal horizontal distance between film frames. Using these criteria, she eliminated the Palmer method and the hip joint from possible use.

Although Beck ruled out the use of the hip joint because it yielded a fairly flat flight path, no evidence was given that the identification of body landmarks during the pilot study or final data collection was controlled. Horizontal and vertical lines drawn through the hip joint served as referent axes from which the calculated center of gravity was located. With only slight deviation, the center of gravity during the run was found anterior and superior to the hip joint. Unfortunately, the actual horizontal and vertical distances of the center of gravity from the hip joint were not given.

Teeple (52), with the aid of a computer program, also used the segmental method to find the center of gravity in female runners. More recently, Osterhoudt (50) selected the hip joint as representative of the center of gravity, while Fenn's (28) weight center location was slightly superior to the hip joint. An adaptation of Palmer's formula was used by Clouse (47) for her study of preschool boys. Morton (9) indicated that because the body's weight center was so close to the hip joints, man's bipedilism was predominantly an interaction between the force of gravity and man's lower extremities. His locomotion studies of walking considered the hip joint as the body's center of gravity.

In summary, it may be seen that investigators have used various methods to determine the location of the center of gravity of the standing body. As it is difficult to find the weight center in the moving body, the hip joint has apparently been justifiably used to represent this location when studying runners in the sagittal plane. Because some investigation suggested that the center of gravity was anterior and superior to the hip joint, the anterior superior iliac crest might also serve as representative of the body's weight center.

SUMMARY

A review of literature from past to present depicts a progressive improvement in techniques to solve essentially the same problems in understanding the mechanics of running. While the contact phase in running has been studied in some detail as a sub-problem, seldom was it the focus of observation. While speculation continues on the effect of speed on various biomechanical factors, there is a demand for research in which running velocity changes are controlled within individuals.

Investigators have frequently studied children in developmental studies and also members of physical education classes, however the skilled runner has been relatively neglected.

CHAPTER III

METHODOLOGY

This study was made in an effort to determine the effect of velocity changes on foot placement, the angle of body lean, and the segmental inclinations of the upper leg, the lower leg, and the foot during the contact phase in running.

In this chapter is found a precise description of each stage involved in the execution of this study.

GENERAL PROCEDURES

This investigation consisted of a cinematographical analysis of skilled runners during the contact phase. Each runner was filmed individually while running at maximum and two submaximum velocities. The film was then analyzed for selected biomechanical factors at three velocities.

The stages of the study were as follows: selecting subjects, determining velocities, collecting data and analyzing data. All procedures were carried out at the University of Windsor.

SUBJECTS

The subjects used in this study were volunteers from the undergraduate and graduate Physical and Health Education programs at the University of Windsor. All runners were also members of the University Track Team and one subject had represented Canada in Olympic competition. Subjects were selected on the basis of recent competition in and training for high caliber track events. The age of the subjects ranged from 20 to

30 years with a mean age of 23.3 years. Data on the speed of the subjects may be found in Appendix B, page 79 .

DETERMINING RUNNING VELOCITIES

By means of time trials the maximum velocity of each runner was found. Finding maximum velocity was necessary to determine the submaximum velocities which were calculated as percentages of this velocity for each subject. The percentages of maximum velocity served as a means of discriminating changes in biomechanical factors studied during the contact phase.

Time Trials

Four sprints of 100 yards distance were performed by the subjects running individually at maximum speed. To attempt to eliminate the problem of skill factor in starting, the subjects had a five yard running start, but were timed from the instant they passed the starting line. A 10 minute recovery period was allotted between trials.

In addition, the subjects were timed during the 4 trials at different selected 10 yard intervals. Physical education students, experienced with stopwatches, recorded the time for runners to pass each interval end marker. Two timers were stationed at each interval marker and the mean time from the two readings was recorded. Interval times were found by subtracting the time recorded for the start of the interval from that recorded for the end of the interval. The lowest mean time to complete a 10 yard interval was used to calculate each runner's maximum velocity. The location along the track in which a runner achieved maximum velocity during an all-out effort in the hundred-yard dash was also determined so that this velocity could be best duplicated during filming.

Submaximum Velocities. Sixty-six and 33 percent of each runner's maximum speed were arbitrarily selected as submaximum speeds. These speeds were used to set the speed-pacer for each runner.

DATA COLLECTION

The collection of data by means of high speed photography involved the use of photographic equipment and speed-pacer, the identification of subjects, the use of measurement controls and anthropometric identification.

Photographic Equipment

The electrically driven, 16 millimeter camera,(HY-CAM, Model K20S4E) used in this study was set to run at 320 pictures per second. This speed permitted detailed observation of contact. To reduce parallax the camera was fitted with a telephoto lens and positioned 75 feet from the center of the running lane and perpendicular to the path of motion. The camera, mounted on a Hercules tripod, was set to film the left side of the body, and was adjusted so that the center of the lens was 36.5 inches above the ground. Five hundred feet of Kodak Tri-X Reversal Film (Type 7278) with an ASA of 200 were required for filming 9 subjects. To ensure proper camera speed the camera was started before the runner entered the photographic view. Optimal weather permitted excellent lighting for filming.

Speed-Pacer. To enable runners to maintain submaximum velocities during filming, a speed-pacer was utilized. A white cord with black sponge markers was drawn over pulleys, one of which was driven by an electric drill which was connected to a variable transformer to serve as a pacer. (See Figure 1, page 24) The pulleys were 4 feet above the ground and the cord was stretched 107 feet along the track to run beside the runner. Each subject was instructed to maintain a constant distance between himself and one of several black markers spaced at equal intervals along the cord. A number of practice trials were performed at each submaximum speed before filming so that runners would follow the speed-pacer without difficulty.

The speed-pacer was guaged for speeds from 3.2 to 27.0 feet per second. The pacer was calibrated to insure submaximum speeds for both the practice and film trials. Calibrations were performed by using a stopwatch to measure the time for the sponge markers to travel a fixed distance.

Subject Identification

Within the photographic field, two sets of marker cards indicated the trial number and the number assigned to each subject.

Origin and Scale Factor

An origin was established by placing, in the bottom left hand corner of the filming area, a long white board with a thin black cross. The origin, formed by the intersection of the vertical and horizontal black lines, was later used as a reference point from which all coordinates were measured for each frame of film. The white background formed by 4 sheets of plywood (4 X 8 feet) contained black markings 1 foot in length placed at two foot intervals. These markings were necessary to calculate the ratio of real to projected length.

Anthropometric Landmarks

To facilitate accurate location of the joints and other anthropometric landmarks, markings, consisting of black squares of electrician's tape on white adhesive tape, were placed on the surface of the skin directly over the landmark. These markings were placed on: the anterior superior iliac crest, the greater trochanter, the lateral femoral condyle and the lateral malleolus, as shown in Figure 2, page 25. In addition, black markings were placed on the tragus as well as the toe of the footwear of the runner. Minimal clothing was worn so that all markings would be plainly visible during film analysis. All runners wore racing swim suits, with the sides rolled, and track spikes. No socks or shirts were worn.

DATA ANALYSIS

Data were extracted from selected film sections containing the contact phase at the three velocities.

Film Analysis

A frame by frame analysis was performed on each runner at the three velocities beginning with one frame before contact of the left foot and ending a few frames after effective contact. The number of frames analyzed, then, varied from runner to runner and decreased with an increase in velocity. As few as 5 frames for maximum velocity and as many as 35 frames for the slowest velocity were examined. Analysis consisted of deriving the vertical and horizontal coordinates of the anatomical landmarks as well as the point of contact. The part of the foot which contacted the ground was also recorded. Each data sheet for each frame was classified according to its frame number determined from an arbitrarily selected zero frame.

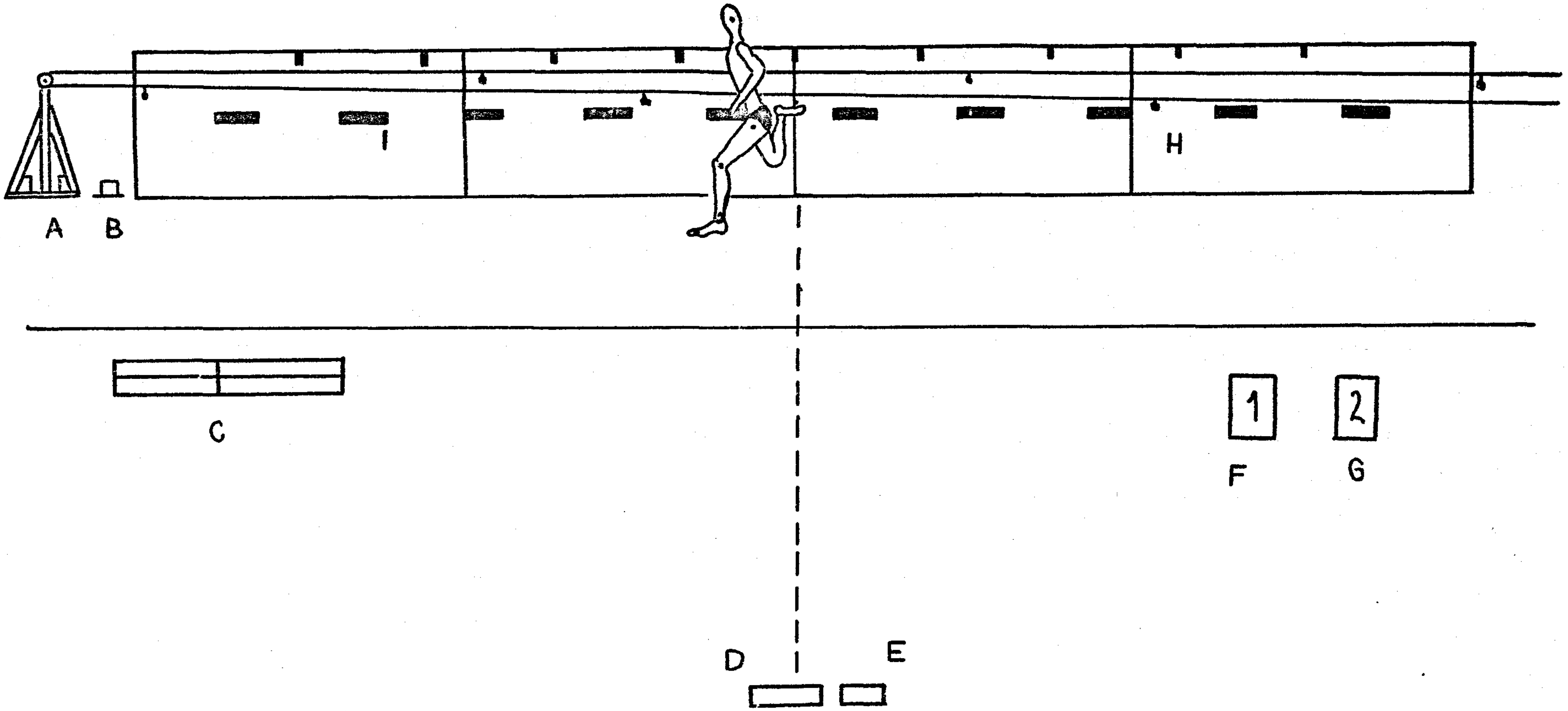

FIGURE 1

SUBJECT RUNNING THROUGH PHOTOGRAPHIC FIELD

A. Speed Pacer
B. Transformer
C. Origin
D. Camera
E. Pulse Generator
F. Subject Number
G. Velocity Indicator
H. Pacer Marker
I. Scale Marker

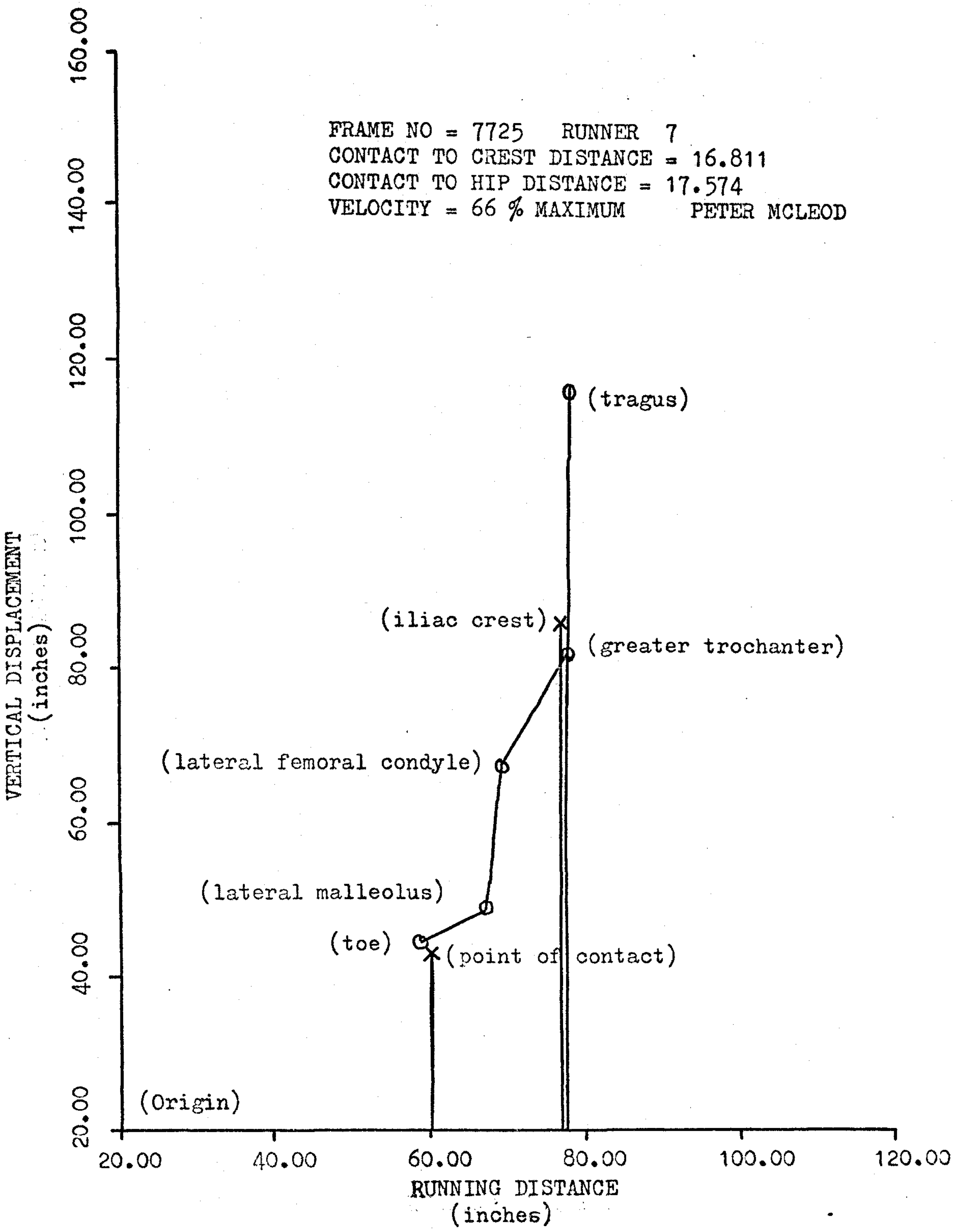

FIGURE 2

THE USE OF ANTHROPOMETRIC LANDMARKS
IN COMPUTER PLOTTING

Analysis Equipment. The Vanguard Motion Analyzer used in this analysis was composed of an M-16 projection head and a C-11M projection case with an A-11 angle screen. Magnification of film size to the viewed image was 27X and distortion free within $\frac{1}{4}$ of one percent. Vertical and horizontal crosshairs, positioned by moving handwheels, provided X and Y coordinates which could be read from a micrometer readout window. Coordinates could be read to the nearest .001 inch. All measurements were made from the origin in the left hand corner of the screen. The analyzer permitted focusing, locking of each frame into the same position as the previous frame, single frame advance and frame counting.

Determination of Actual Camera Speed. The camera was set to run at 320 pictures per second. To precisely determine camera speed, a timing light within the camera was connected to a pulse generator to fire at 10 pips per second. The timing light left a small white dot on the edge of the film. True frame rate was found by multiplying the number of frames between two pips by 10. Calculations of selected film sections resulted in a mean frame rate of 308.1 pictures per second.

Methods of Calculation

Coordinates from each of the anthropometric landmarks and the point of contact were found using the Vanguard Motion Analyzer. These coordinates were then fed into the computer which which was programmed to find the horizontal distance from the point of contact to the representative center of gravity, the angle of body lean, the angle of the upper leg, the angle of the lower leg and the angle of the foot. All angles were measured from the horizontal. (See Figure 3) A computer program was designed to determine these values. In addition, the computer was

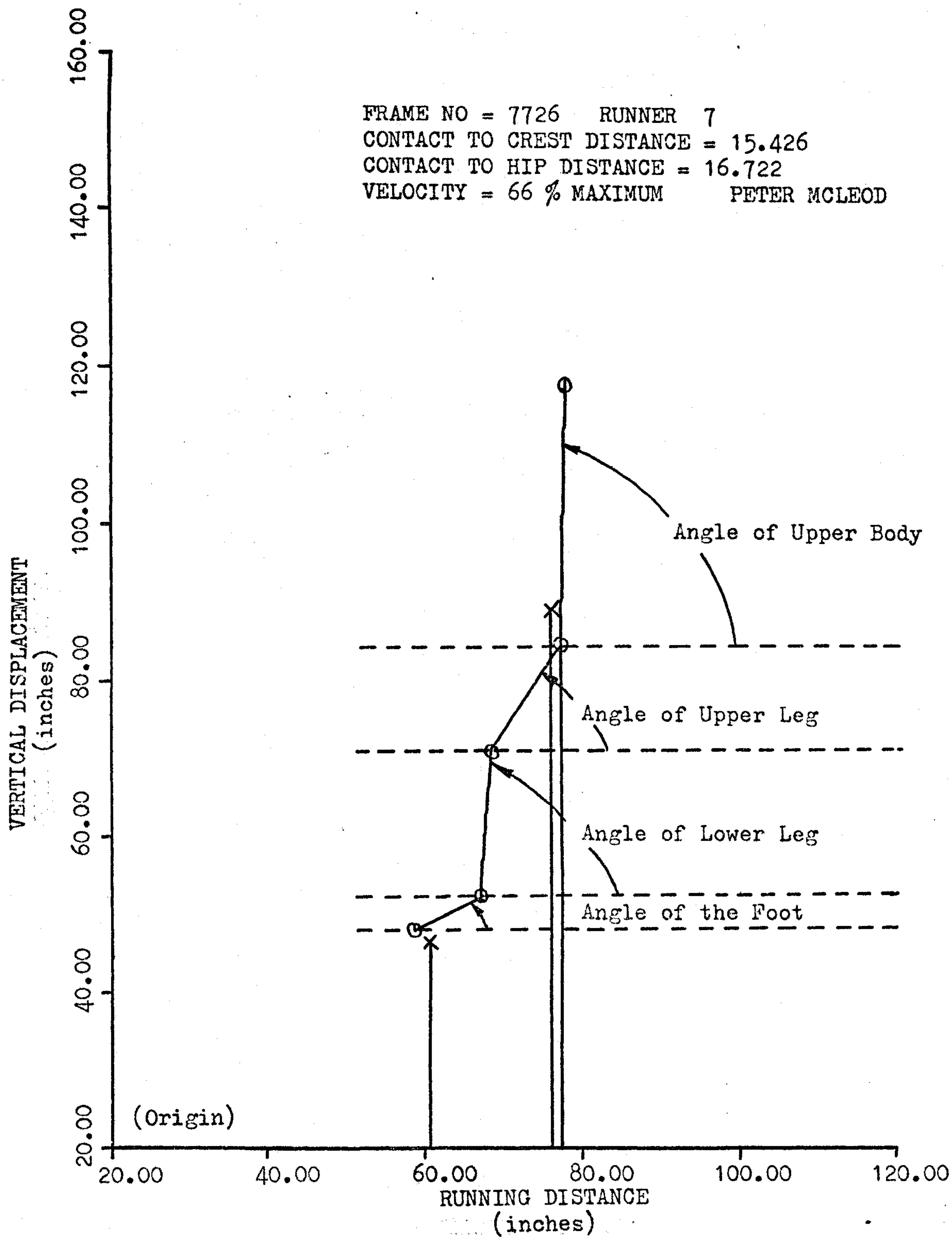

FIGURE 3

MEASUREMENT OF SEGMENTAL ANGLES

programmed to plot a stick diagram of each runner frame by frame to illustrate visually the relationship of these values. The program is reproduced in Appendix A, pages 73-77. In the computer program, 'ear' represents the tragus, 'hip' represents the greater trochanter, 'knee' represents the lateral femoral condyle, 'ankle' represents the lateral malleolus and 'crest' represents the anterior superior iliac crest.

Film Measurement Accuracy. To reduce error in measurement, coordinates taken for all body landmarks were measured twice. Subscripts '1' and '2' were used for the first and second reading of each landmark. The computer was programmed to calculate the mean of these two measures. If the two readings differed by .009 inch, a third reading was made. This error allowance is very small when using the Vanguard Motion Analzer. Even though reading differences seldom reached this maximum allowance, this error when scaled to actual size amounted to only .315 inch.

Representative Center of Gravity. The marker on the greater trochanter served as an anatomical landmark representative of the center of gravity of the body. In addition, the anterior superior iliac crest served as a secondary estimated center of gravity. Measurements were taken by subtracting the abscissa of the contact point from the abscissa of each of these locations. When plotted, a vertical line was dropped from both of the representative centers of gravity.

Point of Contact. The value for the abscissa of the point of contact was considered as the mid-point of the surface area of the foot touching the ground. The position of the mid-point varied throughout contact and was measured as follows:

$$\text{Point of Contact} = \frac{\text{Contact } X_1 + \text{Contact } X_2}{2}$$

The abscissas X_1 and X_2 represent the anterior and posterior extremes respectively of the contact surface.

Angle of Upper Body Lean. The angle of body lean, considered as the hypoteneuse joining the tragus to the greater trochanter, was computed by using the trigonometric tan function as the difference in Y coordinates divided by the difference in X coordinates. Calculations were made as follows:

$$\text{Upper Body Angle} = \text{Arc Tan } \frac{\text{Ear } Y_1 + \text{Ear } Y_2 - \text{Hip } Y_1 - \text{Hip } Y_2}{\text{Ear } X_1 + \text{Ear } X_2 - \text{Hip } X_1 - \text{Hip } X_2}$$

The angle of upper body lean can be found in Appendix B, page 82.

The Angle of the Upper Leg. The hypoteneuse joining the greater trochanter to the lateral femoral epicondyle formed the angle of the upper leg. The method of calculation appears below:

$$\text{Angle of Upper Leg} = \text{Arc Tan } \frac{\text{Hip } Y_1 + \text{Hip } Y_2 - \text{Knee } Y_1 - \text{Knee } Y_2}{\text{Hip } X_1 + \text{Hip } X_2 - \text{Knee } X_1 - \text{Knee } X_2}$$

The angle of the upper leg may be found in Appendix B, page 83.

The Angle of the Lower Leg. The angle of the lower leg was formed by the hypoteneuse joining the lateral femoral epicondyle to the lateral malleolus. Calculations were made as follows:

$$\text{Angle of Lower Leg} = \text{Arc Tan } \frac{\text{Knee } Y_1 + \text{Knee } Y_2 - \text{Ankle } Y_1 - \text{Ankle } Y_2}{\text{Knee } X_1 + \text{Knee } X_2 - \text{Ankle } X_1 - \text{Ankle } X_2}$$

The results of these computations may be found in Appendix B, page 84.

The Angle of the Foot. The foot angle was represented by the hypoteneuse joining the lateral malleolus to the toe and was calculated as follows:

$$\text{Angle of Foot} = \text{Arc Tan} \frac{\text{Ankle } Y_1 + \text{Ankle } Y_2 - \text{Toe } Y_1 - \text{Toe } Y_2}{\text{Ankle } X_1 + \text{Ankle } X_2 - \text{Toe } X_1 - \text{Toe } X_2}$$

Foot angle determinations are recorded in Appendix B, page 85.

STATISTICAL PROCEDURES

One-way analysis of variance, repeated measures, and the Newman Keuls method were the statistical procedures used in this study. Program BMDOIV, from the University of Windsor Computer Library was used to perform the analysis of variance tests. The Newman Keuls method was calculated by means of a desk calculator.

Analysis of variance was computed for each biomechanical factor to determine if differences resulted from variation in velocity. The Newman Keuls method provided a rigorous test of the significance between means. This procedure was used when the F-ratio reached the .05 level of confidence.

CHAPTER IV

RESULTS

This investigation was conducted in an attempt to find the effects of velocity on selected biomechanical factors during the contact phase in running.

The data analyzed in this study is grouped under the following headings: (1) cinematographical determinations, and (2) the effect of velocity during the contact phase.

CINEMATOGRAPHICAL DETERMINATIONS

Measures were taken to find valid camera speed, to bring readings to life size, to ensure the reliability of coordinate readings and to determine the actual velocity of runners and pacer.

Camera Speed

Camera speed was calculated by means of a timing light for those film sections analyzed. A true frame rate of 308.13 with a standard deviation of 1.17 pictures per second was found from 75 determinations.

Film Scale

From measurements of the markings in the background on the film as described on page 22, the ratio of real to projected length was determined. This correction factor was scaled so that one inch on the projected image was equal to 35.503 inches in actual size.

Running Velocity

The velocity of each runner was calculated from the number of frames required for the runner to travel a distance of 24 feet, determined from background markers. The mean speed of the runners at maximum velocity was found to be 30.1 feet per second with a standard deviation of 1.9 feet per second. When compared with a mean of 30.5 ± 3.0 feet per second determined from time trials it may be seen that the subjects actually attained their maximum velocity during filming. For 66 percent maximum running velocity, the time trial determination was 20.0 ± 1.9 feet per second while a mean of 23.8 with a standard deviation of 3.3 feet per second was recorded from film measurements. This would indicate that runners went slightly faster than required during filming.

A time trial value of 10.1 ± 1.0 feet per second was found for 33 percent maximum and may be compared to a value of 11.7 ± 1.3 feet per second determined from the film, which indicates that here, too, the runners went slightly faster than required.

Calculation of actual submaximum velocities from film measures revealed that subjects actually ran percentages of 78.9 and 38.9 rather than 66 and 33 percent of maximum velocity.

Speed-Pacer

From observation of the film it was seen that the runners overtook the speed-pacer markers at the end of the filming area. Calculations show mean speeds of 20.3 and 10.5 feet per second for the speed-pacer or mean percentages of 67.4 and 34.9 of maximum velocity found during the time trials. These values indicate that the speed-pacer operation was quite accurate in regulating submaximum velocities.

THE EFFECT OF VELOCITY DURING THE CONTACT PHASE

In order to determine if running velocity altered the contact phase, various biomechanical factors were observed at three stages of contact; initial contact, effective contact and center of gravity contact.

The Angle of the Upper Body

At initial contact no significant difference was found for the angle of body lean with changes in velocity. As shown in Table I, at the slowest velocity the body deviated only slightly from the perpendicular. During effective and center of gravity contact, however, the upper body lean was significantly greater ($\alpha < .05$) at the maximal than at the slowest velocity. It should be noted that as velocity increased, the standard deviation of mean angle also increased, which indicates that individual differences with regard to body lean are noticeable as speed increases, but are not apparent at the slower velocities.

The mean angle of body lean found for all frames analyzed during contact was 99.5 degrees for maximum velocity, 96.3 degrees for the intermediate velocity and 94.7 degrees for the slowest velocity. Observation of Table X (See Appendix B, page 82) indicates that while some runners showed a slight decrease in body angle, this was not a consistent finding. Some runners for example, exhibited a definite backward lean even at the higher velocities.

The Angle of The Upper Leg

A significant difference ($\alpha < .01$) between maximum and slowest velocity, was found for the angle of the upper leg at initial contact. This meant that the greater the velocity, the more horizontal was the

TABLE I

MEAN ANGLE OF BODY LEAN AT INITIAL, EFFECTIVE AND CENTER OF GRAVITY CONTACT AT THREE VELOCITIES

(degrees)
(N=8)

Contact Phase	Maximum Velocity	Intermediate Velocity	Slowest Velocity	F-Ratio
Initial	97.73	95.17	94.31	1.16
Standard Deviation	5.27	4.93	3.64	N.S.
Effective *	100.41	97.24	94.33	5.13
Standard Deviation	3.20	4.09	3.32	**
C. O. G.	102.05	98.54	93.58	3.47
Standard Deviation	4.56	6.24	8.10	**

* N=7 (Subject Pe. did not exhibit effective contact)

** Significant at the .05 level of confidence

N.S. No significant difference between means

upper leg at contact. A statistically significant difference ($\alpha < .05$) was also found at effective contact, however no differences existed at center of gravity contact. Secondary analysis revealed that these differences also existed only between maximum and slowest velocities. The results showing an increase in the angle of the upper leg at initial and effective contact with an increase in velocity are also seen in Table II.

The Angle of the Lower Leg

At initial contact and at all 3 velocities the angle between the lower leg and the ground was less than 90 degrees in all cases, but one. This angle varied with different velocities, but the difference was not significant except between maximum and intermediate velocities in which case the lower leg was closer to the perpendicular at maximum velocity than at intermediate velocity. These results are seen in Table III, page 37.

As effective contact was defined as contact in which the lower leg was at an angle of 90 degrees to the running surface, this period of contact was not affected by variation in velocity. The fact that the slight deviation from 90 degrees at effective contact as seen in Table III, suggests that even at high camera speeds as used in this study, effective contact could not be precisely determined. Faster camera speeds would be required to locate this phase exactly. The actual angles of the lower leg may be found in Appendix B, page 84.

Without exception, the runner's foot was completely flat when the lower leg was perpendicular. It should be noted that at initial contact, the angle of the lower leg at slowest velocity fell between that at intermediate and maximum velocity. This was the only time that this

TABLE II

MEAN ANGLE OF UPPER LEG AT INITIAL, EFFECTIVE AND CENTER OF GRAVITY CONTACT AT THREE VELOCITIES

(degrees)
(N=8)

Contact Phase	Maximum Velocity	Intermediate Velocity	Slowest Velocity	F-Ratio
Initial	54.60	58.67	65.25	8.41
Standard Deviation	4.95	5.54	5.21	***
Effective *	59.39	61.38	67.10	4.01
Standard Deviation	6.52	4.67	4.44	**
C. O. G.	72.35	73.82	72.48	0.51
Standard Deviation	2.59	3.75	3.24	N.S.

* N=7 (Subject Pe. did not exhibit effective contact)

** Significant at the .05 level of confidence

*** Significant at the .01 level of confidence

N.S. No significant difference between means

TABLE III

MEAN ANGLE OF LOWER LEG AT INITIAL, EFFECTIVE AND CENTER OF GRAVITY CONTACT AT THREE VELOCITIES
(degrees)
(N=8)

Contact Phase	Maximum Velocity	Intermediate Velocity	Slowest Velocity	F-Ratio
Initial	87.03	79.51	83.84	7.88
Standard Deviation	4.50	3.60	3.17	***
Effective *	89.91	90.27	90.28	0.69
Standard Deviation	0.89	1.13	0.28	N.S.
C. O. G.	119.80	119.12	117,83	0.38
Standard Deviation	3.87	5.57	4.00	N.S.

* N=7 (Subject Pe. did not exhibit effective contact)

*** Significant at the .01 level of confidence

N.S. No significant difference between means

phenomenom occurred.

At center of gravity contact the lower leg angles were virtually the same at all velocities.

The Angle of the Foot

There was no difference between the angle of the foot at any stage of contact among the three velocities. These angles are listed in Table IV.

The Position of the Foot. At maximum velocity all runners first contacted the ground on the ball of the foot. There was slight variation in the intermediate and slowest velocities, however all but one runner continued to land on the ball of the foot at intermediate velocity; that runner landed with a heel-first contact. At the slowest velocity 3 runners landed with other than ball contacts; two runners landed with the heel first while one runner landed with a flat foot. Generally, during heel contact, the foot plantar-flexed rapidly, bringing the foot to full flat contact. A list of contacts for all runners is shown on page 88. In all cases the difference in the position of the foot was slight. This probably relates to the fact that the angle of the foot at contact did not alter with a change in velocity.

Relation of Contact to Representative Centers of Gravity

Contact was examined in relation to the iliac crest as well as the greater trochanter. For the purpose of this study, the greater trochanter served as the representative center of gravity. Since several investigators alluded to the anterior superior iliac crest region as a location of the body's weight center, measurements were also made to this point. These measures are shown in Table V and Table VI, page 40.

TABLE IV

MEAN ANGLE OF THE FOOT AT INITIAL, EFFECTIVE AND CENTER OF GRAVITY CONTACT AT THREE VELOCITIES

(degrees)
(N=8)

Contact Phase	Maximum Velocity	Intermediate Velocity	Slowest Velocity	F-Ratio
Initial	13.93	14.76	54.69 **	0.89
Standard Deviation	3.61	6.92	120.71	N.S.
Effective *	15.71	15.88	12.58	1.86
Standard Deviation	3.80	2.76	4.12	N.S.
C. O. G.	25.46	20.05	19.94	1.42
Standard Deviation	8.61	7.92	5.56	N.S.

* N=7 (Subject Pe. did not exhibit effective contact)

N.S. No significant difference between means

** Subject Do. exhibited an angle of 352.74 because his foot was dorsiflexed at initial contact at slowest velocity. This resulted in the large mean foot angle and large standard deviation.

TABLE V

MEAN HORIZONTAL DISTANCE FROM CONTACT POINT TO ILIAC CREST AT INITIAL AND EFFECTIVE CONTACT

(inches)
(N=8)

Contact Phase	Maximum Velocity	Intermediate Velocity	Slowest Velocity	F-Ratio
Initial	15.15	15.62	10.73	5.41
Standard Deviation	2.14	2.87	4.42	**
Effective *	12.02	10.33	8.54	3.03
Standard Deviation	3.01	2.06	2.78	N.S.

* N=7 (Subject Pe. did not exhibit effective contact)

** Significant at the .05 level of confidence

N.S. No significant difference between means

TABLE VI

MEAN HORIZONTAL DISTANCE FROM CONTACT POINT TO TROCHANTER AT INITIAL AND EFFECTIVE CONTACT

(inches)
(N=8)

Contact Phase	Maximum Velocity	Intermediate Velocity	Slowest Velocity	F-Ratio
Initial	17.16	17.49	12.16	6.62
Standard Deviation	2.30	2.88	4.34	***
Effective *	13.96	12.67	10.06	3.73
Standard Deviation	3.48	1.70	2.69	**

* N=7 (Subject Pe. did not exhibit effective contact)
** Significant at the .05 level of confidence
*** Significant at the .01 level of confidence

The Horizontal Distance from Contact to Crest. At initial contact the difference in the horizontal distance from the point of contact to the iliac crest was significantly less with changes in velocity. The faster the running speed the greater the distance between the point of contact and the anterior superior iliac crest. The iliac crest moved towards the point of contact on landing so that during effective contact the horizontal distance from contact to the iliac crest decreased. No significant difference was found for the three velocities at effective contact.

The Horizontal Distance from Contact to Trochanter. Variation in velocity produced significant differences in the horizontal distance from point of contact to trochanter at both initial contact ($\alpha < .05$) and at effective contact ($\alpha < .01$). Secondary analysis showed that these differences existed between maximum and slowest velocities and intermediate and slowest velocities at initial contact and between maximum and slowest velocities at effective contact.

SUMMARY

The results of this study indicate that during the contact phase variations in velocity significantly altered some biomechanical factors while not affecting others. A detailed discussion of the results of this study is included in the following chapter.

CHAPTER V

DISCUSSION

This study has examined the contact phase in running in relation to controlled changes in velocity.

This chapter provides a discussion of the results found in this investigation and is divided into the following headings: (1) general procedure, (2) the effect of velocity on the contact phase, and (3) plotting analysis.

GENERAL PROCEDURE

Subjects

Ten subjects were originally selected to participate in this study. This number was determined on the basis of the cost of the film and film processing. As one subject could not be made available for filming, he was omitted from the later stages of the study. Another subject was filmed late in the afternoon and his results were not included in analysis as lighting did not permit accurate location of the anatomical landmarks.

The 8 runners analyzed consisted of a range from marathon runners to sprinters so that this sample represented a cross-section of runners from different track events. As most of their times for the hundred yard dash were under 11 seconds and the mean time was 10.69 seconds, it would appear that the subjects could be considered skilled runners.

Determining Running Velocities

Although half of the subjects attained maximum velocity between

50 and 60 yards during the time trials, three of the subjects reached this velocity at the 40 to 50 yard interval and one subject achieved maximum speed at the 60 to 70 yard interval. Runners started either 10 yards in front of, or behind the starting line so that runners would be at maximum velocity at the 50 to 60 yard interval for filming.

These results compare favourably with the findings of Ikai (45) who examined male and female sprinters of varying age and skill. Wilt (43) who was also in close agreement with this study, indicated that sprinters reached maximum speed after about 6 seconds. On the other hand, Powell (38) stated that the smaller athlete reached maximum velocity at approximately 40 yards while the more powerful athlete attained top speed at about 45 yards.

Submaximum Velocities. Although the speed-pacer replicated the runners' submaximum speeds, the runners caught up with, rather than followed the speed-pacer. The actual velocities of the runners, though higher than the speed-pacer, still permitted adequate breakdown of maximum velocity into submaximum velocities. Teeple (52) did not report faster speeds by the runners over the pacer, however her results suggested slightly faster speeds by the runners. Increased deviation from pacer speeds appears to come with an increase in velocity.

While the investigations by Teeple (52) and Osterhoudt (50) used fairly short run-ins with the speed-pacer, in an effort to ensure pacer speeds by the runners in this investigation runners were given a lead-in of over 60 feet in length.

Film Measurement Error

The motion of the subjects was measured in the sagittal plane, but since movements in the transverse and frontal planes were also present, some distortion inevitably existed when coordinates were extracted from the film. In addition, it was observed that there was a slight movement of the markers at the surface of the skin over the body landmarks. This apparent movement at the hip and knee may have occurred concomitantly with movement of the lower limb in the frontal plane and was assumed to be a constant error from subject to subject.

Another source of inaccuracy was in the identification of the anthropometric landmarks on the film. The black marker on each landmark, particularly on the iliac crest, was not clearly visible in occasional film frames. In order to overcome this problem a template for each runner was designed to locate these absent markers.

It can be noticed in the continuous plotting diagrams, pages 57-59, that occasionally a stick figure is out of alignment. This is due to the separate focusing of each frame of the film. Because this was not a measurement error and happened infrequently, these figures did not distort the entire plot and were overlooked when viewing the continuous plotting.

THE EFFECT OF VELOCITY ON THE CONTACT PHASE

Upper Body Lean

The evidence from this study suggests that while the angle of body lean may increase slightly with an increase in running velocity, this is not to the extent suggested by many writers of kinesiology. The mean body lean at maximum velocity found in this study was 97.57 degrees, which is considerably smaller than the 115 degree lean recommended by Morehouse and Cooper (8) for sprinting. The results of this investigation, then, also deviate from statements by Rasch and Burke (11), Soule (42), and Jensen and Shultz (7). This investigation also partially contradicts the findings of Osterhoudt (50) who showed that at contact, body lean increased as speed increased.

The relatively erect position of the trunk for all running, recommended by Slocum and James (41) and Dyson (6) would be supported in this study, particularly for the slower running velocities. These results also support those by Teeple (52) who, using the line joining the ear and hip as the angle of body lean, found mean upper body angles of 99.41, 96.41 and 95.07 degrees for maximum, intermediate and slowest speeds respectively.

It appears from the evidence gathered in this investigation that body lean angle changes during the contact phase. At the initial contact stage no significant difference was found in the angle of body lean with different velocities, but at other stages of contact forward body lean increased significantly with an increase in velocity. This relationship is shown in Figure 4. One suggestion for this fluctuation in body lean during the contact phase might be that it results from slight rocking action of the upper body over the contacting foot as the upper body 'catches up' with the lower limbs.

Another possible explanation is that it is related to the transfer of force. Since, at the initial contact stage, no significant difference in angle of body lean was found with an increase in velocity, it might seem plausible that no forward lean is required while the body is exerting minimal or no force upon the ground, as in flight. During later stages of contact, however, in which force is applied to the ground, body lean might assume biomechanical importance, possibly in absorption

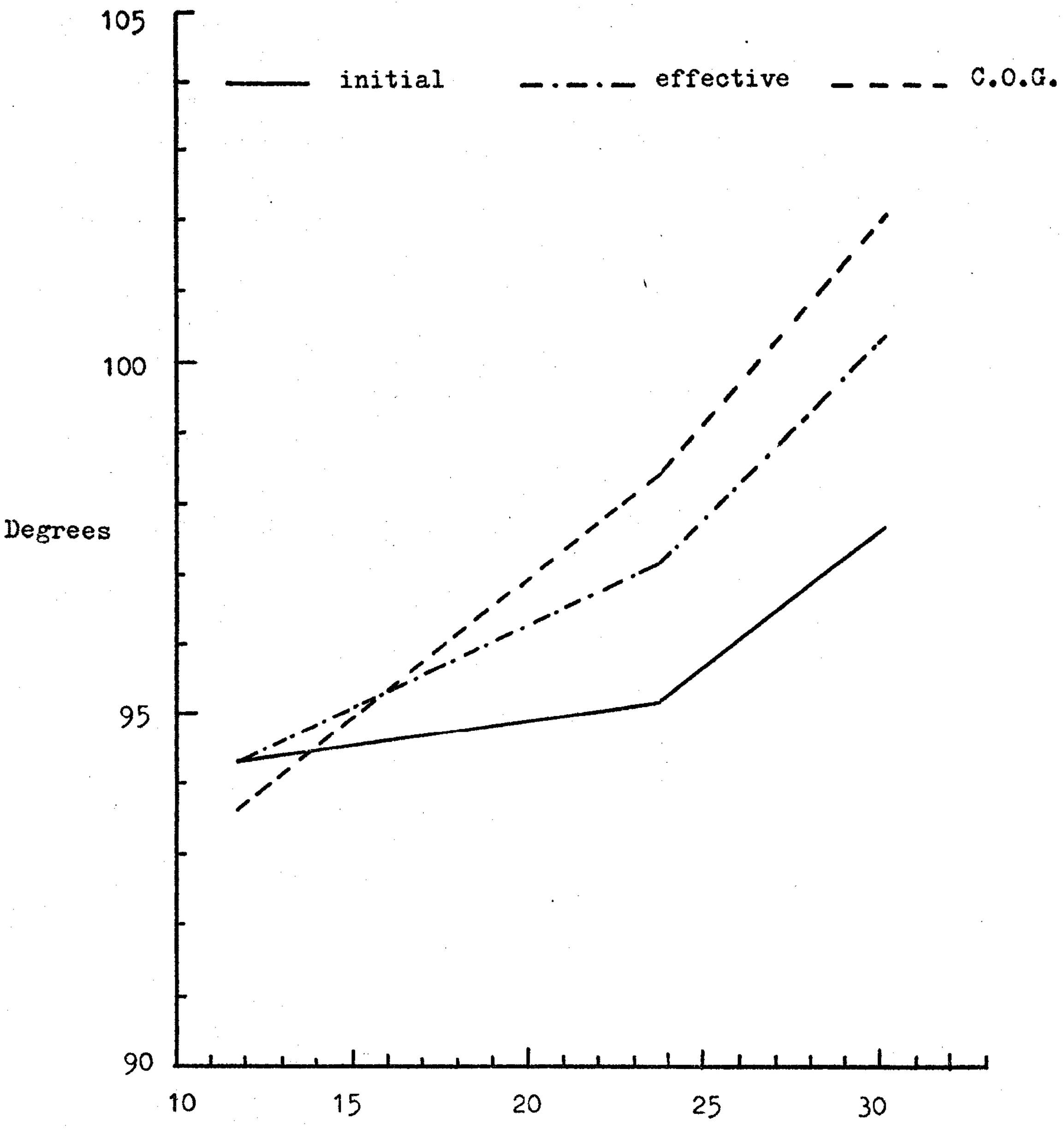

FIGURE 4

ANGLE OF BODY LEAN AT THREE CONTACT STAGES
AT THREE VELOCITIES

of impact or in forward propulsion of the body in the early stages of take-off.

While it would seem that this slight increase in forward lean is imperceptible to the naked eye, the extent of forward lean for all running phases may be distorted by observing runners only during these later stages of contact, as Dyson (6) suggested.

Angle of the Upper Leg

In this investigation, the angle of the upper leg became more horizontal at contact with an increase in velocity. This relationship is shown in Figure 5. Although her subjects may have been too young to compare with the runners used in this study, Clouse (47) also found that with increased running skill, the angle of the thigh approached a more horizontal position at contact.

As can be seen from Figure 3, page 27, the angle of the upper leg could be considered as a measure of knee-lift. During the contact phase, of course, the knee is being lowered from a peak height and the angle of the upper leg just prior to initial contact is increasing from a minimum value. With this in mind, the results of this study give an indication of greater knee-lift with increasing velocity previous to the moment of contact and support the results of Deshon and Nelson (22) and Fortney (49) who examined knee-lift during other stages of the running pattern. Teeple (52), however, found low correlations between angle of leg lift and running velocity.

Angle of the Lower Leg

At initial contact the angle of the lower leg ranged from approximately 74 to 91 degrees. Only one runner exhibited a lower leg angle

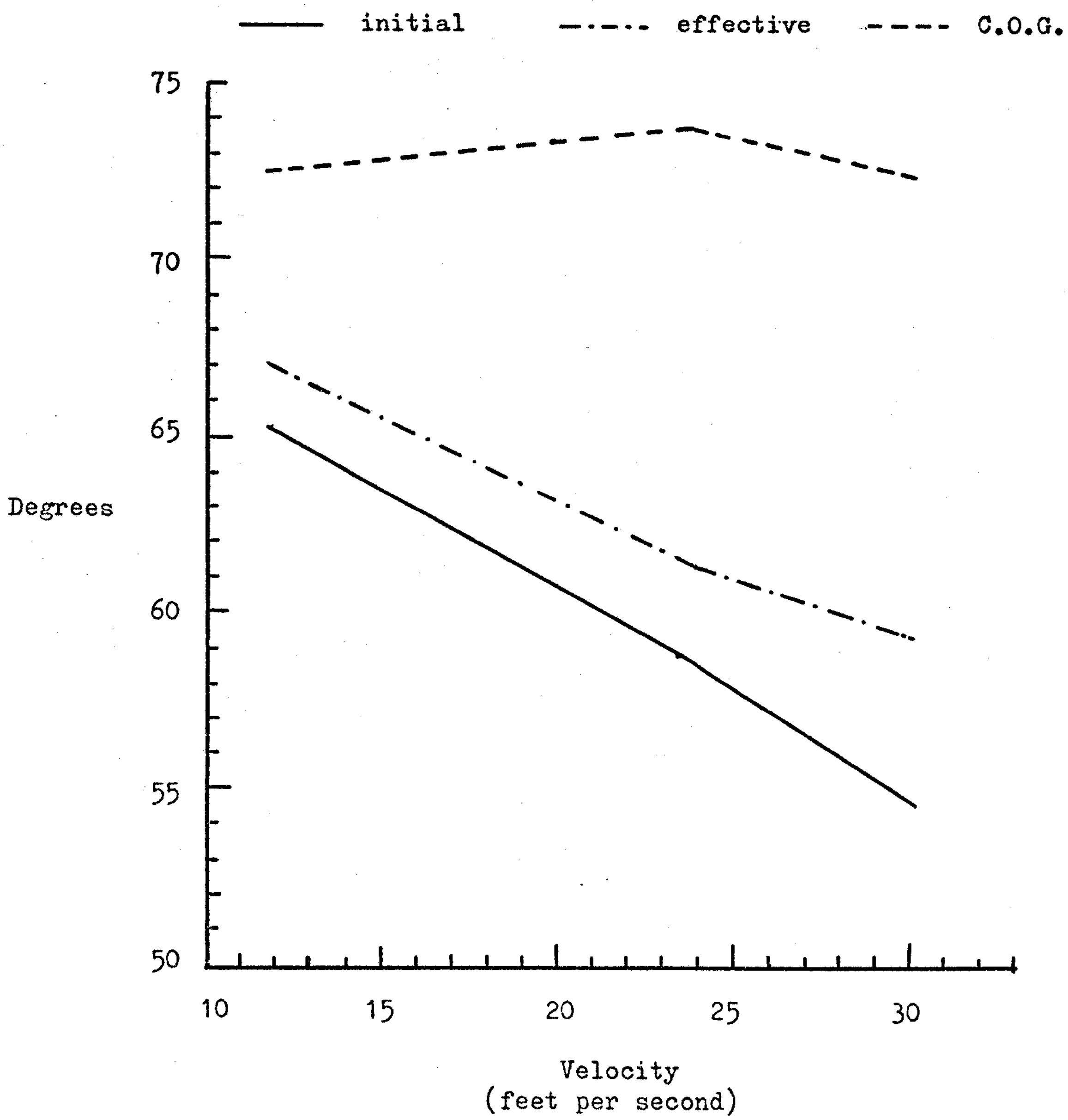

FIGURE 5

ANGLE OF UPPER LEG AT THREE CONTACT STAGES
AT THREE VELOCITIES

greater than 90 degrees and only one runner yielded a lower leg angle of less than 77 degrees. This is shown in Figure 6.

Teeple (52), in close agreement with this study found that at touchdown, the angle of the lower leg was approximately 80 to 90 degrees. Osterhoudt (50) reported that the angle of touchdown was between 80 to 90 degrees for submaximum velocities and that this angle was greater with higher speeds. While Hogberg (30) indicated that the angle of touchdown was vertical, Fenn (27) reported a mean angle of 76.5 degrees. Hogberg's findings disagree with other investigations possibly because his analysis was performed using a treadmill. The discrepancy found in Fenn's study may be related to an inability to determine initial contact when vision of the contact foot was hidden by the lattice-work construction used in his study. Another possibility is that running style may have changed sufficiently in the last 50 years to effect the angle of the lower leg.

The mean angle of the lower leg at center of gravity contact, when the greater trochanter was directly over the point of contact, was almost identical for all velocities. As the upper leg during this stage exhibited this same phenomenom, this may be an indication first, of the consistency of segmental inclination of the upper and lower leg during the driving phase of varying velocities in running, and second, a suggestion of the biomechanical consistency of all running.

After finding that runners lost momentum during foot contact, Fenn (28) indicated that by getting his foot directly under his center of gravity, a runner might reduce this retarding force. Similarly, Slocum and Bowerman stated, ". . . A simple force diagram will reveal that the farther ahead of the body the foot strikes the ground, the more

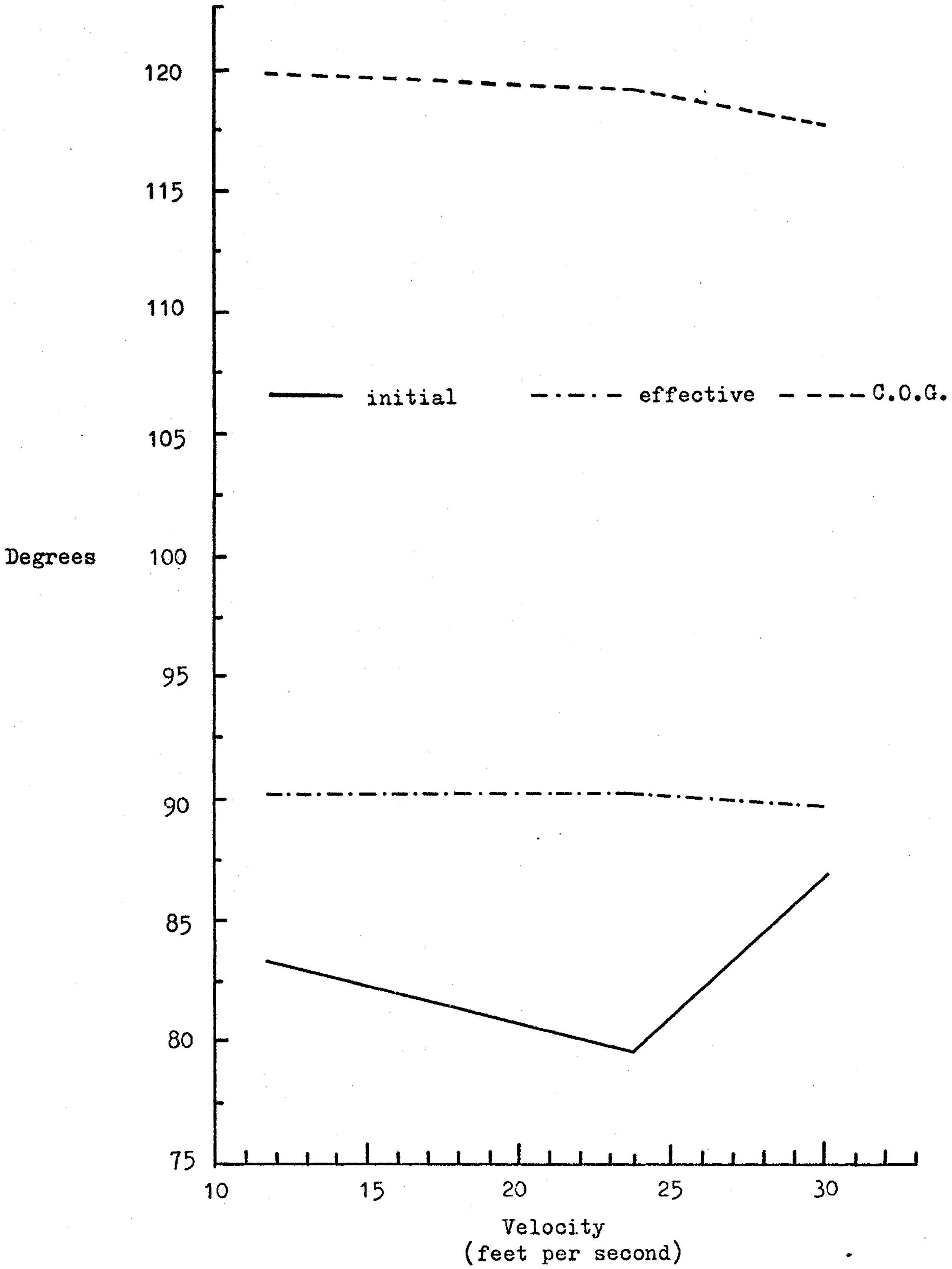

FIGURE 6

ANGLE OF LOWER LEG AT THREE CONTACT STAGES
AT THREE VELOCITIES

acute the angle of the leg with the ground and the greater the deceleration from ground resistance . . . ." (40:43)

Although it might seem that running efficiency could be increased by landing with the leading leg closer to the perpendicular, the results of this investigation indicate that there is no difference between the angle of the lower leg between slowest and maximum velocity. Teeple (52) who also examined a range of running velocities found that the angle of touchdown was not related to running velocity. On the other hand, Deshon and Nelson (22) studying maximum velocity found a statistically significant relationship between velocity and the mean angle of touchdown. It should be noted, however, that the angle of touchdown was considered as the line joining the malleolus to the center of gravity rather than the malleolus to the knee.

Position of the Foot

Observation of contact revealed the difficulty in assessing the most meaningful measure of the angle of the foot. Many runners who landed with a toe slightly dorsiflexed, particularly when first contacting the ground with the heel, yielded foot angles that did not best describe the inclination of the entire foot. Selection of the sole of the foot, one alternate method of measure, might also be misleading in that little information would be gained on the movement of the joints during contact.

The findings from this investigation suggest that foot contact does not necessarily become more flat-footed with a decrease in velocity. The full-foot contact observed by other investigators may have resulted from the type of running surface used in testing. While Fenn (27) had subjects run on both concrete and turf, Hogberg (30) based his observations on subjects running on a treadmill. The subjects used in this study who ran on an all-weather track appear to have closely demonstrated the "universally applicable technique" discussed by Nett (35) in which a biomechanical factor may be applied to all running velocities. In teaching beginners, for example, runners could be instructed to run on the balls of the feet independent of the velocity or distance they are running.

Contact and the Representative Center of Gravity

If the two anatomical landmarks, the iliac crest and the greater trochanter, are considered as representative of the center of gravity of the body, then, it would appear that the evidence obtained in this investigation might be in opposition to some beliefs regarding the position of the body's weight center during the contact phase. In the first place, the contact foot did not seem initially to land directly under the center of gravity of the body as suggested by Wilt (44), but approximately 17 to 12 inches in front of the trochanter. Second, this distance decreased to a mean of approximately 12 inches when the lower leg was at an angle of 90 degrees to the running surface. Third, the horizontal distance from contact to the center of gravity did not decrease with an increase in speed.

Evidence of this can be found in Figures 7 and 8, pages 53 and 54, which indicates that the slower the running velocity, the closer is the center of gravity to the point of contact. Osterhoudt (50), filming at 160 frames per second, measured the horizontal distance from the heel to the hip at contact. His results supported the results of this study as

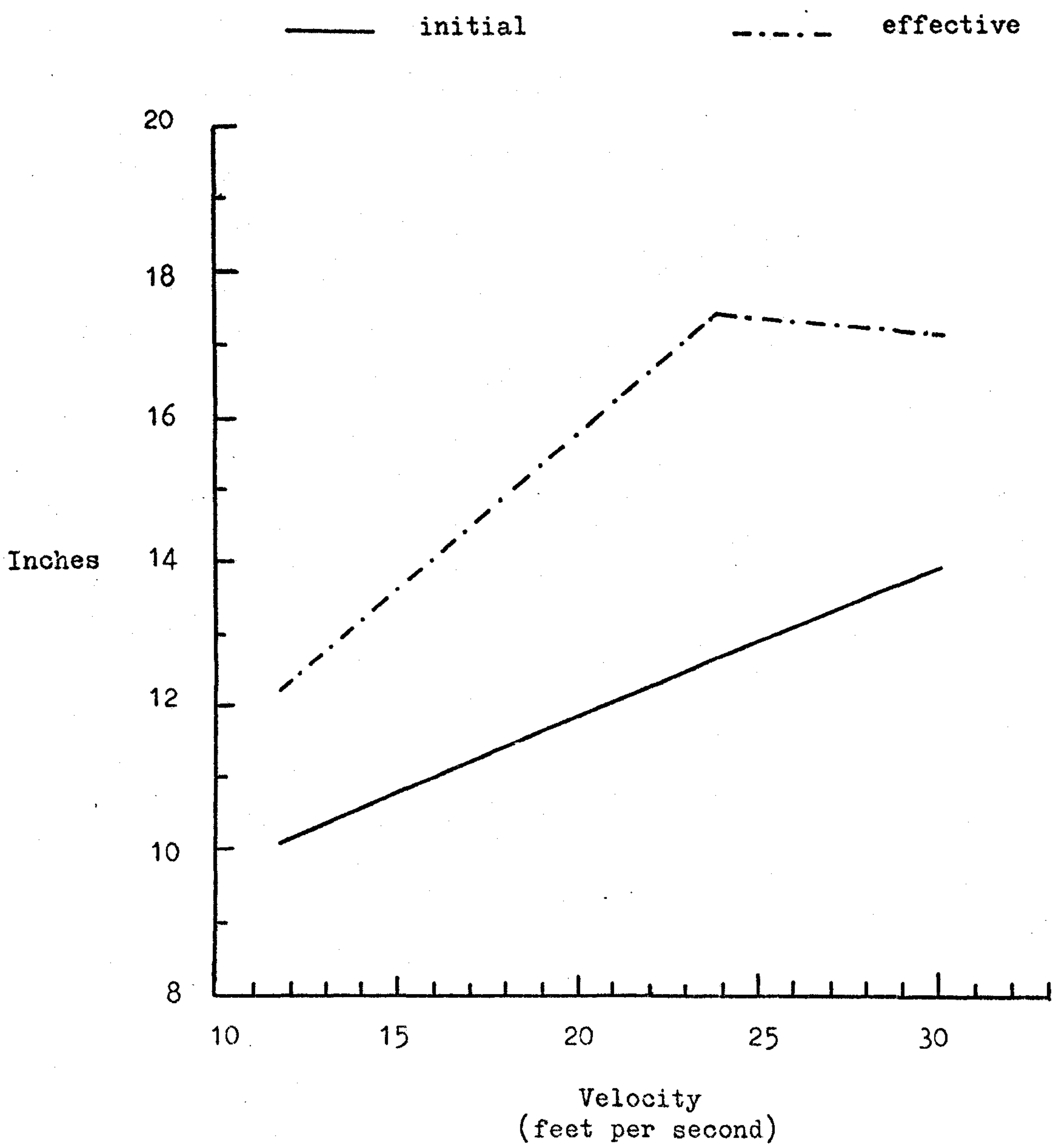

FIGURE 7

HORIZONTAL DISTANCE FROM CONTACT TO TROCHANTER AT INITIAL AND EFFECTIVE CONTACT AT THREE VELOCITIES

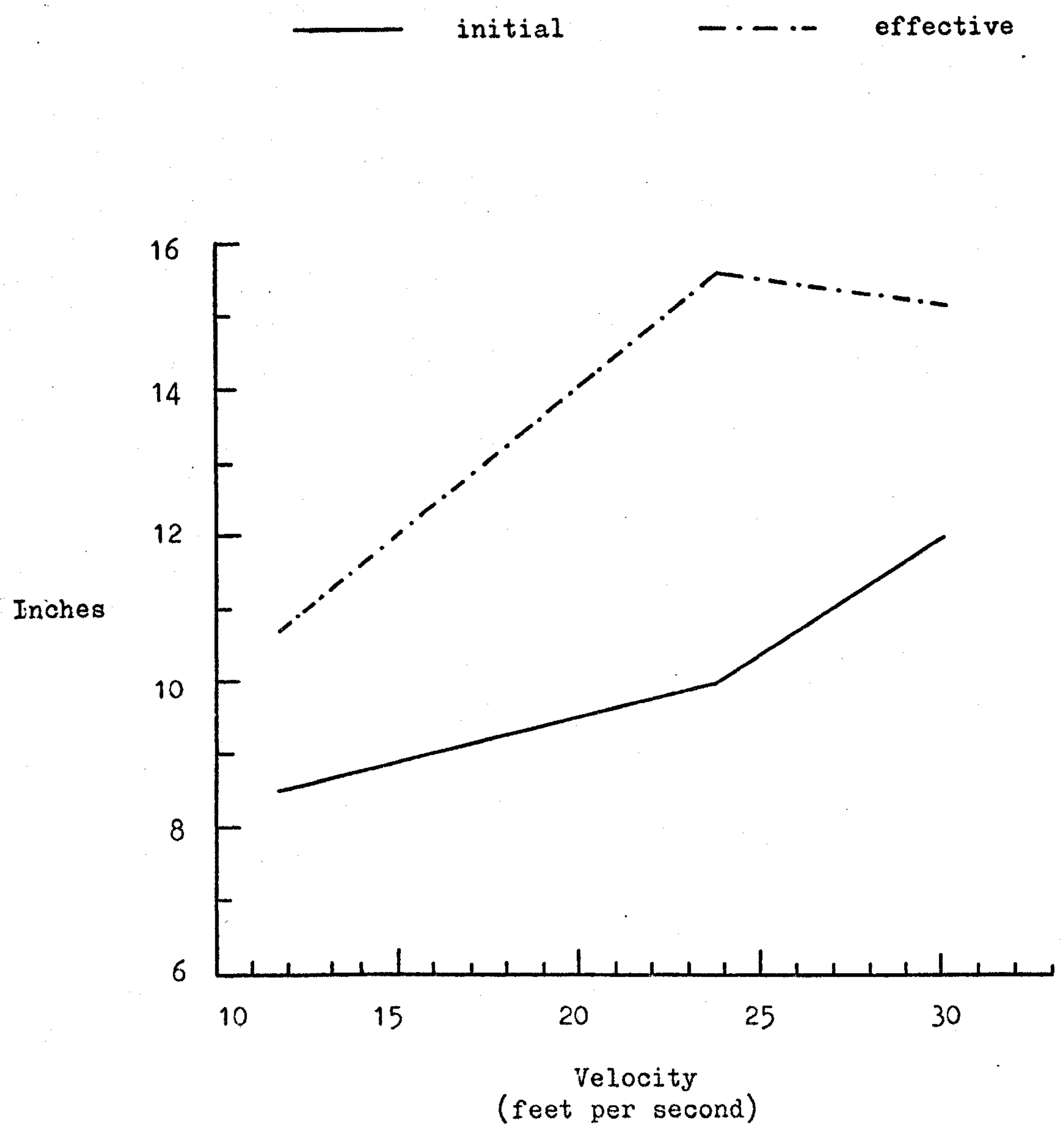

FIGURE 8

HORIZONTAL DISTANCE FROM CONTACT TO ILIAC CREST
AT INITIAL AND EFFECTIVE CONTACT
AT THREE VELOCITIES

this distance decreased with a decrease in running velocity.

It should be noted that the point of contact (which was a mean of the total foot surface contacting the ground) changed constantly during the contact phase. During heel and ball contacts, the point of contact moved forward and backward respectively as the contact phase progressed. This factor might normally be neglected during casual observation with the naked eye or using films taken at slower camera speeds.

Because initially the point of contact is ahead of the center of gravity, it seems conceivable that there is a potential period in which the lower limb could offer a 'pulling' force as suggested by Dyson (6). This concept of pulling the body over the point of contact, similar to the 'pawing' action in running described by Bunn (2), has been disputed by Wilt (44) apparently on the basis that the runner places his front leg on the ground directly under the center of gravity. Although Fenn (28) found that the contact point was ahead of the body's weight center for about 0.03 seconds, in this study a higher value was found. The evidence from this investigation indicates that this potential period of pull could last from 0.052 to 0.072 to 0.108 seconds for the the three velocities examined. If the period in which 'pull' was exerted lasted only as long as the lower leg was at an acute angle with the ground, then, this potential period of 'pull' could last from 0.01 to 0.02 to 0.03 seconds for the fastest to slowest velocities examined in this study.

It would seem that such a short period of time would be negligible in sprinting events, however in marathons, if such a 'pulling' force did exist, it appears possible that there could be some contribution to the forward motion of the runner. During the contact phase, the runner's momentum is likely more important than any possible 'pulling' action in order to bring the runner's center of gravity over the contact foot.

PLOTTING ANALYSIS

The Ankle Joint

Analysis of continuous frame by frame plotting of runners at all 3 velocities revealed the importance of the ankle joint during the contact phase. Its function appears to be two-fold; first, in rotation, and second, in shock absorption.

Rotation. In Figures 9, 10 and 11, pages 57-59, it may be observed that for any one velocity, the angle of body lean and the angle of the upper leg stay relatively constant as depicted by the parallel lines joining the tragus to trochanter and the trochanter to the knee. While movement at the hip joint is negligible, the flexion at the knee and particularly at the ankle is considerable. The rotation of the lower leg over the ankle joint, seen in the computer plotting from one subject and typical of all subjects, begins immediately upon contact and continues until center of gravity contact. This relationship may also be seen in Figure 12, page 60.

Cooper and Glassow (3) observed rotation at the ankle joint in Herb Elliot, who landed with a flat foot, but indicated that at 0.03 seconds into contact, the initiation of ankle extension prevented further rotation. Analysis of the plotting performed on the runners in this study suggests conflicting findings as even at intermediate speeds ankle rotation lasted a mean of 0.072 seconds. Further examination of later

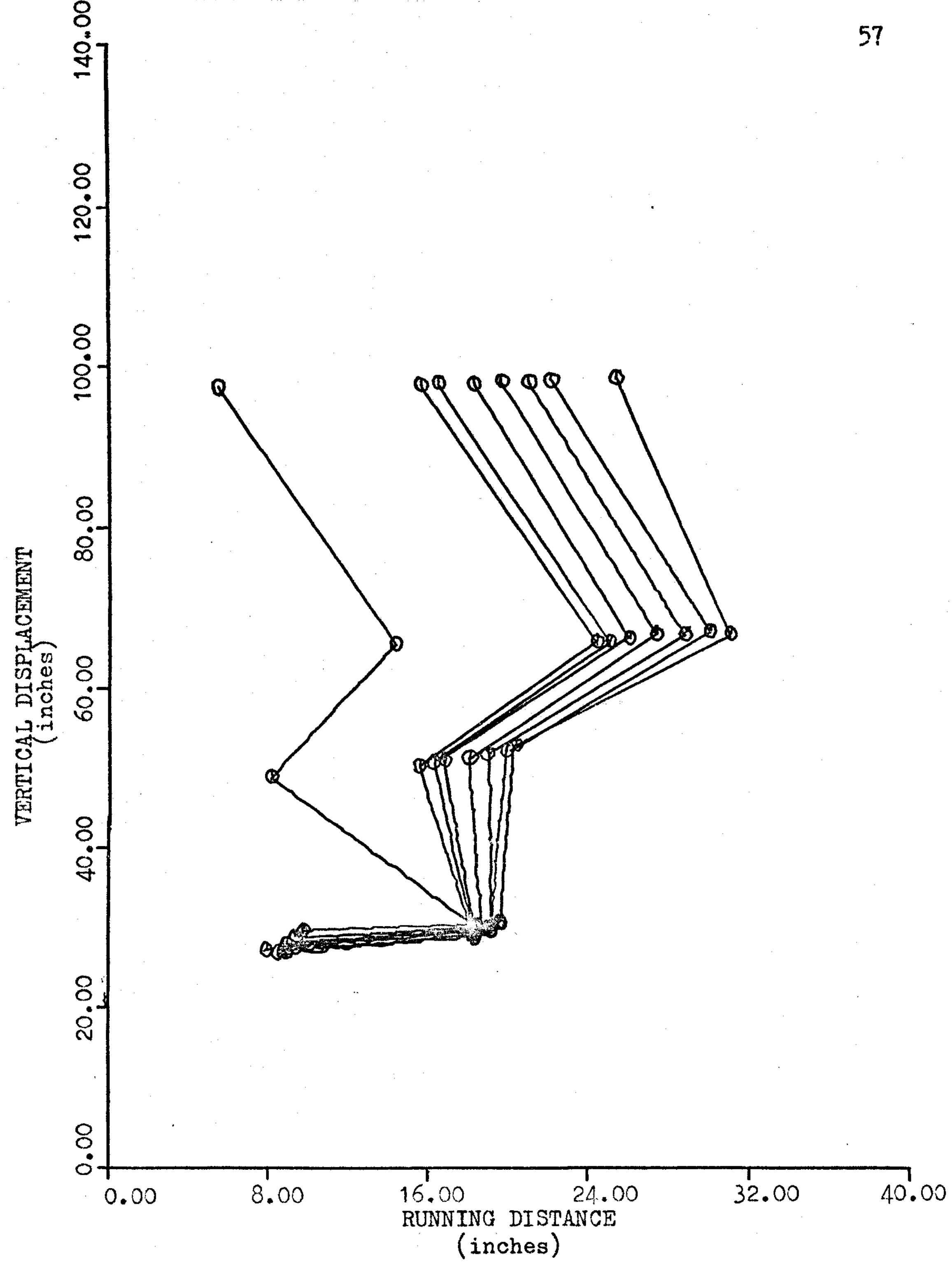

FIGURE 9

CONTINUOUS PLOT OF SUBJECT FROM INITIAL TO BEYOND EFFECTIVE CONTACT AND A DISCRETE PLOT OF CENTER OF GRAVITY CONTACT AT MAXIMUM VELOCITY

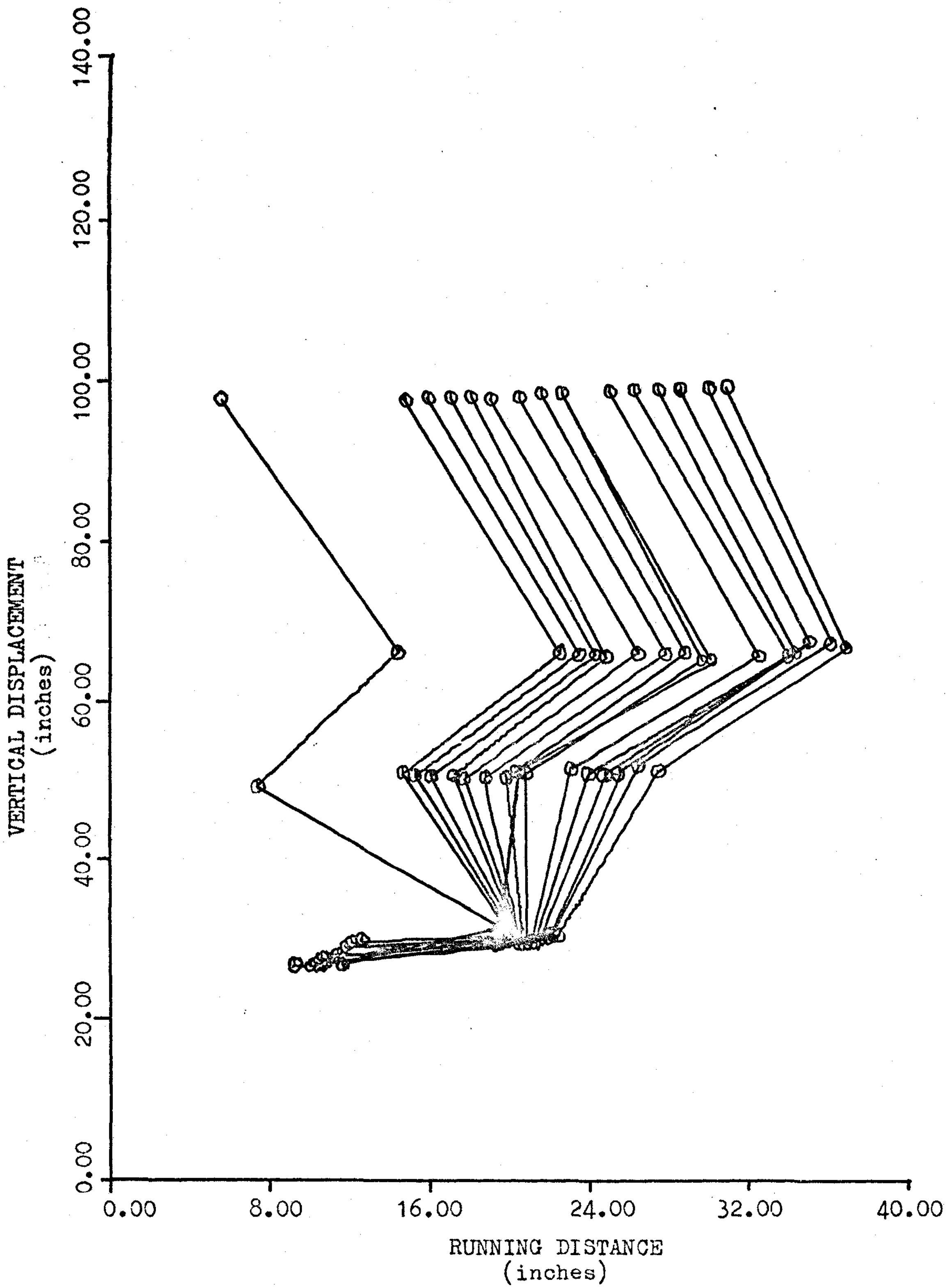

FIGURE 10

CONTINUOUS PLOT OF SUBJECT FROM INITIAL TO BEYOND EFFECTIVE CONTACT AND A DISCRETE PLOT OF CENTER OF GRAVITY CONTACT AT INTERMEDIATE VELOCITY

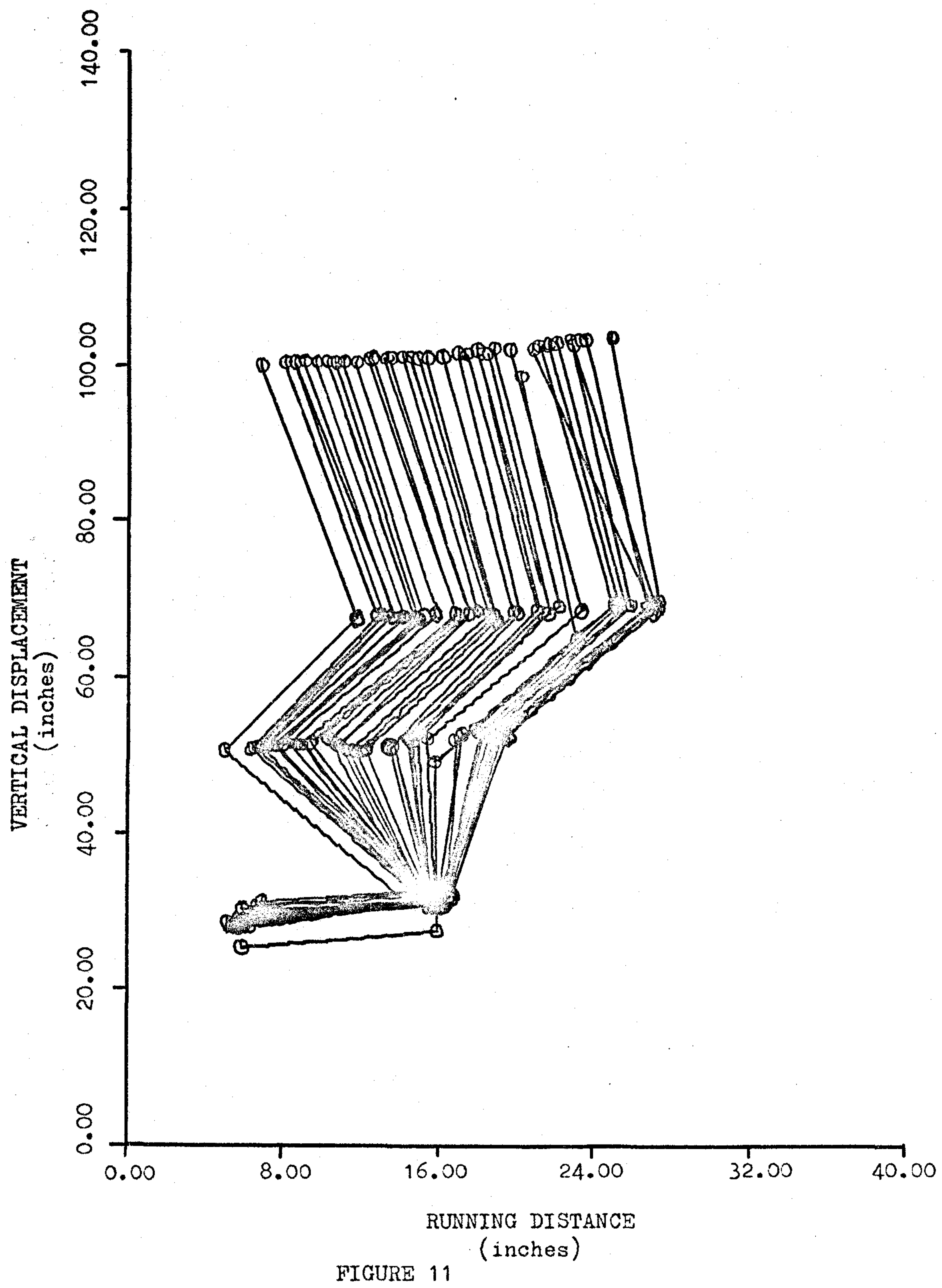

FIGURE 11

CONTINUOUS PLOT OF SUBJECT FROM INITIAL TO BEYOND EFFECTIVE CONTACT AND A DISCRETE PLOT OF CENTER OF GRAVITY CONTACT AT SLOWEST VELOCITY

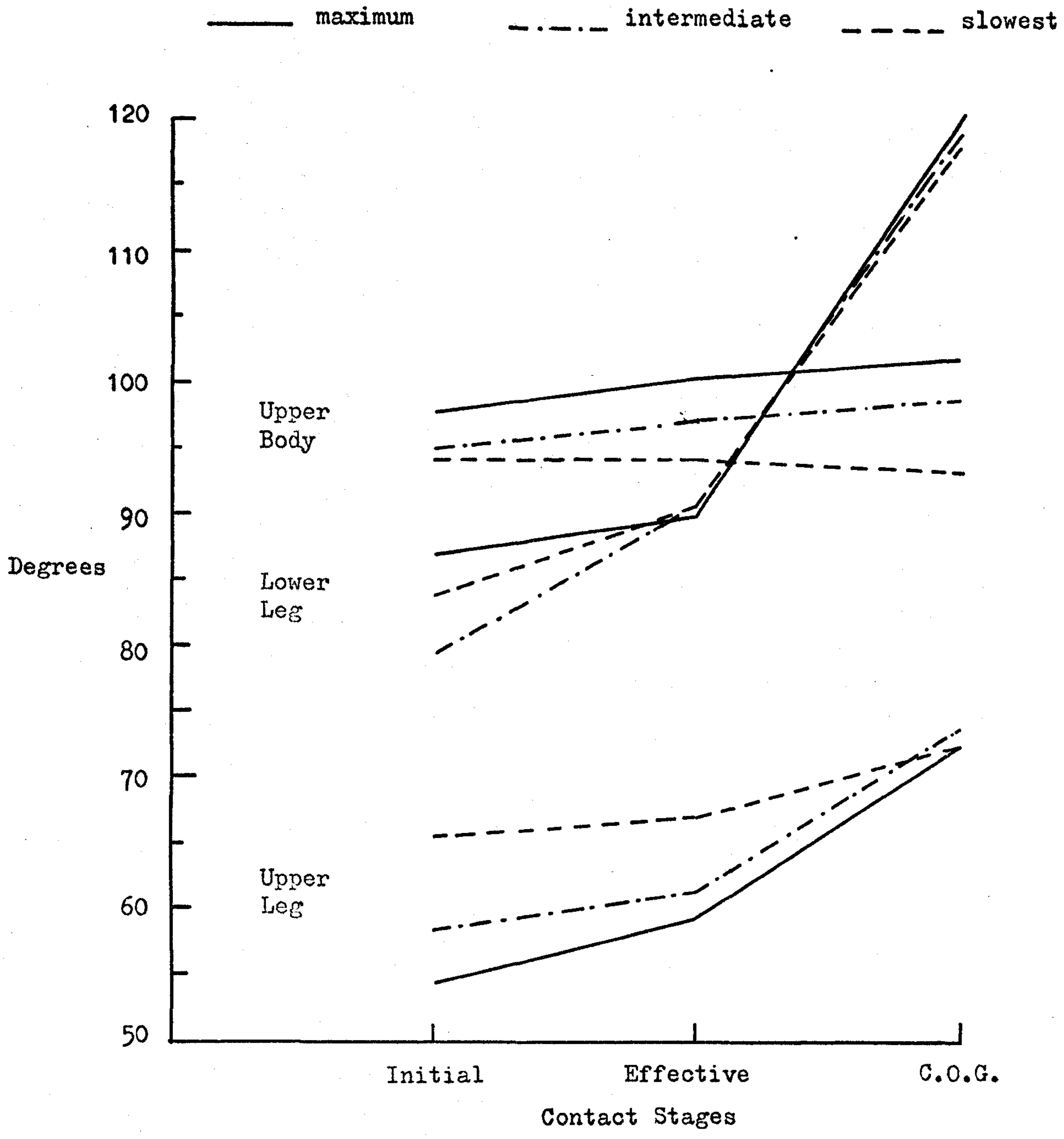

FIGURE 12

CHANGE IN SEGMENTAL ANGLES DURING CONTACT FOR THREE VELOCITIES stages of contact until take-off would undoubtably illustrate this relationship to an even greater extent.

Although Fortney (49) found flexion of the hip and knee during the entire contact phase in good performers, her subjects were aged from 7 through 11. The evidence from runners in this study might suggest that changes in either skill level and/or maturity could reduce both knee and hip flexion at contact.

The emphasis by Slocum and James (41) on the importance of dorsiflexion in leg length adjustment may be misleading. Rather than allowing the lower leg to pivot over one axis of the foot as they suggested, it seems more likely that double axes, one at the point of contact and the second at the ankle joint are active as the body passes over the contacted surface.

Shock Absorption. By means of ankle rotation, as seen in the stick diagrams, it seems that the ankle may be vital in absorbing the impact of the body on contact and lessening resistance to avoid deceleration.

Investigators have generally repeated Fenn's (28) claim that there is always slight bending of the knee to break the shock as the weight of the body comes on to the foot, however little mention is made of the role of the ankle. It would appear that the ankle action is more effective potentially, than the relatively negligible bending of the knee, in transferring vertical to horizontal components of force upon contact. As the segmental angle change of the upper leg is minimal, it appears that bending of the knee is a direct result of rotation of the lower leg over the ankle.

Hubbard (33) felt that distance runners could avoid soreness in the calf of the leg if taught to run flat-footed. The results from this investigation suggest that during the slowest velocities, when there is a greater tendency for flat-footed contact, the runner becomes increasingly dependent upon the ankle for absorption of impact. During flat-footed contact, when there is no perceptible flexion at the knee, and probably very little absorption by the heel, the ankle must be of major importance during contact to cushion impact.

Inter-Study Differences

Several factors, not examined in this study, may be responsible for the discrepancies between this report and others. Some of these are: (1) little previous investigation has been made with subjects of sex, maturity, skill level and training experience similar to those of this study, (2) seldom have studies used high speed photography or analyzed data with sophisticated equipment, and (3) few examinations have examined a wide range of running velocities.

CHAPTER VI

SUMMARY AND CONCLUSIONS

This investigation examined the effect of velocity changes on selected biomechanical factors on skilled runners during the contact phase.

SUMMARY

In this study, 8 male track athletes were filmed while running at 3 velocities on an all-weather track. Focus was placed on the relationship of the point of contact of the leading foot to anthropometric landmarks, representative of the center of gravity of the body. The other factors examined were: the angle of upper body lean; angle of the upper leg; the angle of the lower leg and the position of the foot.

This study examined the left side of the body in the sagittal plane on film taken at approximately 308 pictures per second. All testing, filming and analysis were performed at the University of Windsor.

The procedures followed to study contact were: the selection of subjects; the determination of maximum and submaximum velocities; a filming phase in which runners were photographed at maximum speed and at two submaximum speeds; and a data collection phase in which coordinates of anthropometric landmarks were extracted from selected film frames.

A computer program was designed to calculate the horizontal distance from the point of contact to the representative centers of gravity, and to compute the body segmental angles. An ancillary program plotted stick figures for each frame analyzed and grouped selected frames to illustrate the sequential pattern of the body movement during contact.

One-way analysis of variance was utilized for each biomechanical factor observed to determine if a significant change occurred as a result of an increase in running velocity. When F-ratios reached the .05 level of confidence, a secondary analysis was performed on the means for each velocity by utilizing the Newman Keuls method. Both the .05 and .01 level have been reported.

Based on the above analysis the following findings were determined:

1. Although no differences existed at initial contact between the angle of the upper body lean, with changes in velocity, there was a significantly greater body lean with increased velocity during later stages of contact.

2. The angle of the upper leg decreased with a change from maximum to slowest velocity at initial and effective contact.

3. The angle of the lower leg at initial contact was the only factor that showed a significant difference between intermediate and maximum velocity. When the lower leg was perpendicular, the runner's foot was most completely in contact with the ground.

4. No significant difference was found between the angle of the foot with an increase in velocity at the three contact phases examined.

5. Significant differences between maximum and slowest velocity and intermediate and slowest velocity were found for the horizontal distances between contact to crest and contact to trochanter at initial contact. At effective contact, increasing from slowest to maximum velocity produced a significant decrease in this distance.

Plotting analysis revealed the following observations:

1. Dorsiflexion of the ankle is considerable at contact, while movement about other joints is minimal.

CONCLUSIONS

Within the confines of this investigation, the following conclusions appear to be justified:

1. With a decrease in running velocity, foot contact is made more closely under the representative center of gravity (the greater trochanter and the iliac crest).

2. The angle of upper body lean may increase with an increase in velocity during middle and later stages of contact, but this lean varies among runners and deviates only slightly from the perpendicular.

3. The angle of the upper leg is significantly more horizontal in the early stages of contact at maximum velocity than at slowest velocity.

4. The angle of the lower leg ranges from approximately 74 to 91 degrees at contact. There is no difference in the mean angle of touchdown between maximum and slowest velocities, however, individual differences are great.

5. Dorsiflexion of the ankle is extremely important in cushioning the impact of the body at initial contact, particularly during heel and flat-footed running.

6. During contact, movement of the hip joint is minimal in the frontal plane.

Recommendations for Further Study

To broaden understanding of the effect of velocity on biomechanical factors during contact, study should be made using a greater number of submaximum velocities within the range used in this investigation.

It may also prove valuable to compare the results of this study to data obtained from unskilled runners, in order to isolate factors required for efficient running.

By filming in the frontal plane, a more complete view of the foot at contact may be obtained.

Further detailed analysis of the contact phase should also include the period of contact from center of gravity contact to take-off.

The fluctuations in the angle of the upper body lean during the contact phase may be evident during other running phases. Study of this phenomenom might clarify present beliefs about the role of body lean in running.

Finally, the development of better research techniques could also improve data extraction in cinematography. For example, the design of a template that could accurately locate the center of joints or various anthropometric landmarks when placed over a projected image would facilitate film analysis. Similarly, film analysis would be enhanced by the development of a method that could rapidly determine the location of the center of gravity of the moving body when some limbs are not in view.

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APPENDIX A

COMPUTER PROGRAM

```
      REAL KNEEX,KNEEY
      COMMON/XDATA/EARX(100),HIPX(100),KNEEX(100),ANKX(100),
     1 TOEX(100), CRESTX(100),CONTX(100)
      COMMON/YDATA/EARY(100),HIPY(100),KNEEY(100),ANKY(100),
     1 TOEY(100),CRESTY(100),CONTY(100)
      DIMENSION ANGBOD(100),ANGUL(100),ANGLL(100),ANGFT(100),
     1 S(100), T(100), IBUF(1024)
      INTEGER CONT,ALL/'CONT'/,DISC/'DISC'/,BOTH/'BOTH'/,
     1 NONE/'NONE'/,VEL
      COMMON/SPEED/VEL(20)
      CALL PLOTS(IBUF, 1024)
      READ(5,8) CORR
  1   FORMAT (4I3)
 50   READ(5,4,END=60) VEL
  4   FORMAT(20A4)
      READ(5,3) INF,N,NSTEP,NRUN
  3   FORMAT(I5,3I3)
      DO 20J = 1, N
      READ(5,8) FEARX,FEARY,SEARX,SEARY, FHIPX,FHIPY,SHIPX,
     1 SHIPY,FKNEEX,FKNEEY,SKNEEX,SKNEEY,FANKX,FANKY,SANKX,
     2 SANKY,FTOEX,FTOEY,STOEX,STOEY,FCRX,FCRY,SCRX,SCRY,
     3 FCONX,FCONY,SCONX,SCONY
  8   FORMAT (4F10.0)
      EARX(J) = (FEARX + SEARX)/2.0          *CORR
      EARY(J) = (FEARY + SEARY)/2. 0         *CORR
      HIPX(J)=(FHIPX+SHIPX)/2.               *CORR
      HIPY(J)*(FHIPY+SHIPY)/2.               *CORR
      KNEEX(J) = (FKNEEX + SKNEEX)/2.0       *CORR
      KNEEY(J) = (FKNEEY + SKNEEY)/2.0       *CORR
      ANKX(J) = (FANKX + SANKX)/2.0          *CORR
      ANKY(J) = (FANKY + SANKY)/2.0          *CORR
      TOEX(J) = (FTOEX + STOEX)/2.0          *CORR
      TOEY(J) = (FTOEY + STOEY)/2.0          *CORR
      CRESTX(J) = (FCRX + SCRX)/2.0          *CORR
      CRESTY(J) = (FCRY + SCRY)/2.0          *CORR
      CONTX(J) = (FCONX + SCONX)/2.0         *CORR
      CONTY(J) = (FCONY + SCONY)/2.0         *CORR
      ANGBOD(J)=ARCTAN((EARY(J)-HIPY(J)),(EARX(J)-HIPX(J)))
      ANGUL(J)=ARCTAN((HIPY(J)-KNEEY(J)),(HIPX(J)-KNEEX(J)))
      ANGUL(J)=ARCTAN((KNEEY(J)-ANKY(J)),(KNEEX(J)-ANKX(J)))
      ANGFT(J)=ARCTAN((ANKY(J)-TOEY(J)),(ANKX(J)-TOEX(J)))
      T(J)=HIPX(J)-CONTX(J)
      S(J)=CRESTX(J) - CONTX(J)
      IF (.NOT. ( MOD (J,50 ) .EQ. 0.OR.J.EQ.1)) GO TO 21
      WRITE ( 6,12 ) NRUN
      WRITE (6,13 ) VEL
      WRITE (6,24 )
 24   FORMAT ( '0', T32, 'CALCULATED BODY ANGLES (DEGREES)',
     1 T101,'DISTANCES')
      WRITE (6,25 )
 25   FORMAT( '0', 'FRAME', T11, 'UPPER BODY', T31, 'UPPER
     1 LEG', T51, 'LOWER LEG', T73, 'FOOT', T83, 'CONTACT TO
     2 CREST', T108, 'CONTACT TO HIP')
 21  IFRAME=INF+(J-1) *NSTEP
```

```
20     WRITE ( 6,26  ) IFRAME , ANGBOD (J), ANGUL (J), ANGLL
     1 (J), ANGFT(J), S(J), T(J)
26     FORMAT(' ',I5,6X,4(F7.2,12X),F7.3,12X,F7.3)
       DO 10 J = 1 , N
       IF (.NOT. ( MOD (J,50 ) .EQ. 0.OR.J.EQ.1)) GO TO 11
       WRITE ( 6,12 ) NRUN
12     FORMAT ('1', T20, 'RUNNER NUMBER = ' I2)
       WRITE ( 6,13 ) VEL
13     FORMAT ( ' ' , T20, ' VELOCITY ' , 20A4 )
       WRITE ( 6,14 )
14     FORMAT ('o', T47, 'AVERAGED X-Y COORDINATES FROM INPUT
       DATA')
       WRITE ( 6,15 )
15     FORMAT ('o', 'FRAME',T13, 'EAR', T31, 'HIP', T46,
     1 'KNEE', T61, 'ANKLE', T78, 'TOE', T90, 'ILLIAC CREST',
     2 T105, 'CONTACT POINT')
11     IFRAME=INF+(J-1)*NSTEP
10     WRITE (6,16 ) IFRAME, EARX(J), EARY(J), HIPX(J), HIPY
     1 (J),KNEEX(J), KNEEY(J), ANKX(J), ANKY(J), TOEX(J),
     2 TOEY(J), CRESTX(J), CRESTY(J), CONTX(J), CONTY(J)
16     FORMAT ( ' ', I5, 14F8.3 )
       READ(5,4) CONT
       IF(CONT. EQ. NONE) GO TO 6
       IF(.NOT.(CONT. EQ. ALL. OR. CONT. EQ. BOTH)) GO TO 7
       CALL CPLOT (NRUN,N)
       IF(CONT.EQ.ALL) GO TO 6
 7     READ(5,3)M,L
       IF(L.LT.NSTEP) L=NSTEP
       L=L/NSTEP
       M=M-INF+L
       DO 5 I = M,N,L
       IFRAME = INF +(I -1) *NSTEP
 5     CALL DPLOT (I, IFRAME,S(I), NRUN,T(I))
 6     GO TO 50
60     STOP
       END


       REAL FUNCTION ARCTAN(Y,X)
       REAL PI/3.141593/
       ARCTAN=90.0
       IF(ABS(X).LT.0.00001. AND.Y.GT.0.0) RETURN
       ARCTAN=270.0
       IF(ABS(X).LT.0.00001.AND.Y.LT.0.0) RETURN
       A=ATAN2(Y,X)
       IF(A.LT.0.0) A=A+2.0*PI
       ARCTAN=A*180.0/PI
       RETURN
       END


       SUBROUTINE CPLOT (NRUN,N)
C      SUBROUTINE TO PLOT PICTURES AS ACTUAL TIME SEQUENCE
       REAL KNEEX,KNEEY
       COMMON/XDATA/EARX(100),HIPX(100),KNEEX(100),ANKX(100),
     1 TOEX(100), CRESTX(100),CONTX(100)
```

```
      COMMON/YDATA/EARY(100),HIPY(100),KNEEY(100),ANKY(100),
     1 TOEY(100),CRESTY(100),CONTY(100)
      INTEGER VEL
      COMMON/SPEED/VEL(20)
      DIMENSIONX(4),Y(4),YARRAY(7),XARRAY(7)
C     INITIALIZE PEN POSITION 1  INCH ABOVE BOTTOM
      CALL PLOT (0.,-11.,-3)
      CALL PLOT (o.,1.0,-3)
C     FIND LARGEST X AND Y CO-ORDS OF TOTAL DATA.
      X(1)=0.0
      Y(1)=0.0
      X(2)=0.0
      Y(2)=0.0
      DO 1 J=1,N
      X(1) = AMIN1(EARX(J),HIPX(J),KNEEX(J),ANKX(J),TOEX(J),
      X(1) )
      X(2) = AMAX1(EARX(J),HIPX(J),KNEEX(J),ANKX(J),TOEX(J),
      X(2) )
1     Y(2) = AMAX1(EARY(J),HIPY(J),KNEEY(J),ANKY(J),TOEY(J),
      Y(2))
      WIDTH=FLOAT(N/2)+FLOAT(MOD(N,2))/2.0
      CALL SCALE (X,WIDTH, 2,1)
      CALL SCALE (Y, 7.0, 2,1 )
      CALL AXIS (0.0, 0.0, 'RUNNING DISTANCE', -16,WIDTH,0.0,
     1 X(3), X(4))
      CALL AXIS (0.0, 0.0, 'VERTICAL DISPLACEMENT', 21, 7.0,
     1 90.0, Y(3) Y(4))
      CALL SYMBOL (1.0, 8.5, .14, 'RUNNER', 0.0, 6)
      CALL WHERE (RXPAGE, RYPAGE, RFACT)
      RUN=NRUN
      CALL NUMBER (RXPAGE+.25,8.5,.14, RUN,0.0,-1)
      CALL SYMBOL (1.0,8.0,.14,'VELOCITY =',0.0,10)
      CALL WHERE (RXPAGE, RYPAGE, RFACT)
      CALL SYMBOL(RXPAGE+.25,8.0,.14,VEL,0.0,80)
      XARRAY(6)=X(3)
      YARRAY(6)=Y(3)
      XARRAY(7)=X(4)
      YARRAY(7)=Y(4)
C     PLOT EACH SEPARATE PICTURE SHOWING ACTUAL
C     POSITION EACH TIME OF RUNNER
      DO 2 J = 1,N
      XARRAY(1) = EARX(J)
      YARRAY(1) = EARY(J)
      XARRAY(2) = HIPX(J)
      YARRAY(2) = HIPY(J)
      XARRAY(3) = KNEEX(J)
      YARRAY(3) * KNEEY(J)
      XARRAY(4) = ANKX(J)
      YARRAY(4) = ANKY(J)
      XARRAY(5) = TOEX(J)
      YARRAY(5) = TOEY(J)
2     CALL LINE (XARRAY, YARRAY, 5,1,1,1 )
C     ADVANCE TO NEW PLOT POSITION
      CALL PLOT(WIDTH+12.0,0.0,-3)
      RETURN
      END
```

```
      SUBROUTINE DPLOT(J,IFM,S,NRUN,T)
      REAL KNEEX,KNEEY
      COMMON/XDATA/EARX(100),HIPX(100),KNEEX(100),ANKX(100),
     1 TOEX(100), CRESTX(100),CONTX(100)
      COMMON/YDATA/EARY(100),HIPY(100),KNEEY(100),ANKY(100),
     1 TOEY(100),CRESTY(100),CONTY(100)
      INTEGER VEL
      COMMON/SPEED/VEL(20)
      DIMENSION X(8) , Y(8)
C     INIT PLOT POSITION
      CALL PLOT (0.0,-11.0,-3)
      CALL PLOT (0.0, 1.0, -3)
      X(1) = EARX(J)
      Y(1) = EARY(J)
      X(2) = HIPX(J)
      Y(2) = HIPY(J)
      X(3) = KNEEX(J)
      Y(3) = KNEEY(J)
      X(4) = ANKX(J)
      Y(4) = ANKY(J)
      X(5) = TOEX(J)
      Y(5) = TOEY(J)
      X(6) = 0.0
      Y(6) = 0.0
      CALL SCALE (Y, 7.0, 6, 1 )
      CALL SCALE (X, 5.0, 6, 1 )
      X(6) = X(7)
      Y(6) = Y(7)
      X(7) = X(8)
      Y(7) = Y(8)
      CALL AXIS(0.0,0.0,16HRUNNING DISTANCE,-16,5.0,0.0,X(7),
      X(8))
      CALL AXIS (0.0,0.0,21HVERTICAL DISPLACEMENT,21,7.0,90.0,
      Y(7),Y(8)
      CALL LINE(X,Y,5,1,1,1)
C     DRAW LINE FROM HIP TO X-AXIS
      CALL PLOT ((X(2)-X(6))/X(7),(Y(2)-Y(6))/Y(7),3)
      CALL PLOT((X(2)-X(6))/X(7),0.0,2)
C     PLOT CREST POINT AND CONTACT POINT
      X(1) = CRESTX(J)
      Y(1) = CRESTY(J)
      X(2) = CONTX(J)
      Y(2) = CONTY(J)
      X(3)=X(6)
      Y(3)=Y(6)
      X(4)=X(7)
      Y(4)=Y(7)
      CALL LINE(X,Y,2,1,-1,4)
C     DRAW LINE FROM CREST TO X-AXIS
      CALL PLOT((X(1)-X(6))/X(7),(Y(1)-Y(6))/Y(7),3)
      CALL PLOT((X(1)-X(6))/X(7),0.0,2)
C     DRAW LINE FROM CONTACT POINT TO X-AXIS
      CALL PLOT((X(2)-X(6))/X(7),(Y(2)-Y(6))/Y(7),3)
```

```
      CALL PLOT ((X(2)-X(6))/X(7),0.0,2)
C     PLOT FRAME ID & DISTANCE FROM CREST TO CONTACT
      CALL SYMBOL(1.0,8.7,.14, 'FRAME NO ='  , 0.0, 10)
      CALL WHERE(RXPAGE,RYPAGE,RFACT)
      FM=IFM
      CALL NUMBER(RXPAGE+.25,8.7,.14, FM,0.0,-1)
      CALL WHERE (RXPAGE,RYPAGE,RFACT)
      CALL SYMBOL(RXPAGE +.5,8.7,.14,'RUNNER',0.0,6)
      CALL WHERE (RXPAGE,RYPAGE,RFACT)
      RUN=NRUN
      CALL NUMBER(RXPAGE+.25,8.7,.14, RUN,0.0,-1)
      CALL SYMBOL(1.0,8.4,.14, 'CONTACT TO CREST DISTANCE=
      ' ,0.0,27)
      CALL WHERE (RXPAGE,RYPAGE,RFACT)
      CALL NUMBER (RXPAGE +.25,8.4,.14,S,0.0,3)
      CALL SYMBOL(1.0,8.1,.14,'CONTACT TO HIP DISTANCE =
      ',0.0,25)
      CALL WHERE (RXPAGE,RYPAGE,RFACT)
      CALL NUMBER(RXPAGE+.25,8.1,.14,T,0.0,3)
      CALL SYMBOL(1.0,7.8,.14,'VELOCITY =',0.0,10)
      CALL WHERE (RXPAGE, RYPAGE, RFACT)
      CALL SYMBOL(RXPAGE+.25,7.8,.14,VEL,0.0,80)
C     ADVANCE TO NEW PLOT POSITION
      CALL PLOT(17.0, 0.0, -3)
      RETURN
      END
```

APPENDIX B

BIOMECHANICAL DATA

TABLE VII

MEAN INTERVAL TIME RECORDED DURING TIME TRIALS
(seconds)
(N=8)

Subject	Intervals (in yards)			
	40-50	50-60	60-70	0-100
Ge.	1.08	0.95	1.10	10.14
Do.	1.05	0.98	0.98	9.88
De.	1.08	1.06	1.33	11.35
Al.	1.08	1.12	1.12	11.06
Br.	1.08	1.03	1.07	10.68
Ke.	1.07	1.27	1.05	11.25
Pe.	0.85	1.04	1.06	10.95
Ro.	0.83	1.03	1.03	10.21

TABLE VIII

MAXIMUM AND SUBMAXIMUM VELOCITIES DETERMINED FROM TIME TRIALS AND FROM FILM MEASURES

(feet per second)
(N=8)

Subject	Maximum Velocity		Intermediate Velocity		Slowest Velocity	
	Trial	Film	Trial	Film	Trial	Film
Ge.	31.6	29.2	20.1	26.4	10.5	12.1
Do.	31.6	33.3	20.1	24.2	10.5	10.5
De.	28.3	27.8	18.8	19.7	9.4	12.2
Al.	27.9	28.9	18.6	21.5	9.3	10.5
Br.	29.1	30.0	19.4	22.3	9.7	10.7
Ke.	28.6	28.3	19.0	21.6	9.5	10.9
Pe.	35.5	31.8	23.6	24.1	11.8	12.7
Ro.	36.4	31.6	24.2	30.2	12.1	14.1

TABLE IX

VELOCITY OF SPEED-PACER AT SUBMAXIMUM VELOCITIES
(feet per second)
(N=8)

Subject	Intermediate Velocity		Slowest Velocity	
	Runner	Pacer	Runner	Pacer
Ge.	26.4	19.8	12.1	12.0
Do.	24.2	20.4	10.5	9.4
De.	19.7	18.2	12.2	8.7
Al.	21.5	18.6	10.5	10.0
Br.	22.3	20.2	10.7	9.5
Ke.	21.6	20.0	10.9	10.6
Pe.	24.1	21.9	12.7	11.3
Ro.	30.2	22.9	14.1	12.3

TABLE X

ANGLE OF THE UPPER BODY AT THREE VELOCITIES AND AT THREE CONTACTS

(degrees)
(N=8)

Subject	Maximum Velocity			Intermediate Velocity			Slowest Velocity		
	Initial	Effective	C.O.G.	Initial	Effective	C.O.G.	Initial	Effective	C.O.G.
Ge.	100.39	104.07	105.64	100.78	101.82	105.86	95.42	95.06	98.46
Do.	105.62	104.46	103.97	99.08	99.87	99.07	96.01	95.10	96.48
De.	98.24	100.50	102.16	87.97	89.78	91.09	94.40	93.18	96.35
Al.	97.59	99.49	101.35	96.28	98.01	100.71	92.53	92.93	75.79
Br.	96.05	97.39	104.77	97.41	98.11	102.59	98.82	96.29	98.39
Ke.	93.29	95.82	103.67	91.26	93.85	93.46	87.87	88.51	89.93
Pe.	88.59		91.26	98.37	88.66	90.20	91.31	92.26	91.72
Ro.	102.08	101.16	103.56	99.22	99.27	105.37	98.15	99.21	101.52

TABLE XI

ANGLE OF THE UPPER LEG AT THREE VELOCITIES
AND AT THREE CONTACTS
(degrees)
(N=8)

Subject	Maximum Velocity			Intermediate Velocity			Slowest Velocity		
	Initial	Effective	C.O.G.	Initial	Effective	C.O.G.	Initial	Effective	C.O.G.
Ge.	52.24	56.64	69.40	57.79	57.62	67.43	64.29	64.88	68.27
Do.	50.22	47.74	72.15	53.51	59.84	69.36	69.59	65.05	71.57
De.	64.83	69.65	69.25	70.18	69.55	76.64	72.22	76.10	74.54
Al.	57.22	61.23	71.96	58.72	64.36	76.51	67.37	69.90	76.55
Br.	52.29	60.28	72.27	52.52	55.18	72.06	60.86	64.62	74.56
Ke.	69.73	59.35	76.25	61.94	61.09	76.17	67.08	63.79	73.24
Pe.	56.83		71.60	56.18	62.77	77.36	65.07	54.79	67.24
Ro.	53.46	60.81	75.92	56.14	62.01	75.01	65.07	65.36	73.87

TABLE XII

ANGLE OF THE LOWER LEG AT THREE VELOCITIES
AND AT THREE CONTACTS
(degrees)
(N=8)

Subject	Maximum Velocity			Intermediate Velocity			Slowest Velocity		
	Initial	Effective	C.O.G.	Initial	Effective	C.O.G.	Initial	Effective	C.O.G.
Ge.	88.16	90.74	118.57	78.52	90.00	124.22	81.73	90.19	115.91
Do.	88.33	88.61	117.39	77.77	90.26	114.54	78.42	90.40	116.96
De.	83.04	89.53	115.75	74.05	89.82	113.58	86.53	90.40	111.69
Al.	82.55	90.64	117.63	77.65	89.88	117.44	89.06	89.95	116.08
Br.	82.33	89.28	126.99	82.90	89.94	129.24	84.13	89.88	119.56
Ke.	86.79	90.78	116.86	84.11	89.25	115.59	84.22	90.64	118.33
Pe.	95.72		122.18	77.48	90.47	115.88	84.16	90.71	125.77
Ro.	89.29	89.12	123.00	83.62	92.74	122.50	82.49	90.48	118.38

TABLE XIII

ANGLE OF THE FOOT AT THREE VELOCITIES AND AT THREE CONTACTS
(degrees)
(N=8)

Subject	Maximum Velocity			Intermediate Velocity			Slowest Velocity		
	Initial	Effective	C.O.G.	Initial	Effective	C.O.G.	Initial	Effective	C.O.G.
Ge.	7.58	10.15	19.43	6.32	12.14	28.89	10.11	11.95	18.95
Do.	14.75	15.80	16.96	17.70	19.93	23.64	352.74	10.93	17.61
De.	13.14	19.07	20.90	9.03	15.52	16.31	12.98	13.43	12.01
Al.	15.26	13.90	27.24	19.19	12.62	23.42	8.23	12.43	17.84
Br.	9.98	15.82	45.00	7.07	17.66	12.78	6.93	5.05	19.72
Ke.	15.34	13.51	25.75	14.65	16.43	27.37	3.55	16.75	24.07
Pe.	18.76		23.54	26.36	25.71	5.53	30.66	20.28	31.02
Ro.	16.59	21.72	24.86	17.77	16.86	22.44	12.29	17.46	18.33

TABLE XIV

HORIZONTAL DISTANCE FROM CONTACT TO TROCHANTER AT THREE VELOCITIES AND AT INITIAL AND EFFECTIVE CONTACT

(inches)
(N=8)

Subject	Maximum Velocity		Intermediate Velocity		Slowest Velocity	
	Initial	Effective	Initial	Effective	Initial	Effective
Ge.	20.63	18.62	19.88	13.03	15.53	10.53
Do.	17.93	18.20	20.93	13.35	10.23	10.65
De.	15.05	9.64	16.33	10.03	12.41	8.10
Al.	15.83	11.06	17.70	11.22	6.71	5.56
Br.	18.14	12.25	17.91	13.60	7.65	10.69
Ke.	18.05	12.78	15.53	12.23	9.53	10.60
Pe.	13.30		18.50	15.16	18.23	15.23
Ro.	18.36	15.16	19.14	15.23	16.93	14.31

TABLE XV

HORIZONTAL DISTANCE FROM CONTACT TO CREST AT THREE VELOCITIES AND AT INITIAL AND EFFECTIVE CONTACT

(inches)
(N=8)

Subject	Maximum Velocity		Intermediate Velocity		Slowest Velocity	
	Initial	Effective	Initial	Effective	Initial	Effective
Ge.	18.16	16.21	18.21	10.72	13.81	8.84
Do.	13.44	14.06	15.64	8.45	7.90	8.10
De.	13.19	7.92	14.38	8.81	11.68	6.92
Al.	13.60	8.81	15.27	8.93	4.70	4.05
Br.	17.20	12.44	10.35	12.39	6.87	9.62
Ke.	15.78	10.78	14.20	9.23	8.33	9.04
Pe.	12.78		17.24	13.94	16.03	13.79
Ro.	17.02	13.94	19.70	13.79	16.51	13.21

TABLE XVI

TYPE OF INITIAL CONTACT AT THREE VELOCITIES (N=8)

Subject	Maximum Velocity	Intermediate Velocity	Slowest Velocity
Ge.	ball	ball	ball
Do.	ball	ball	heel
De.	ball	ball	ball
Al.	ball	ball	ball
Br.	ball	heel	flat-foot
Ke.	ball	ball	heel
Pe.	ball	ball	ball
Ro.	ball	ball	ball

APPENDIX C

FORMS

SUBJECT DATA SHEET

SUBJECT #

NAME ______________________________

AGE ____________

PHONE NUMBER ______________________

ADDRESS ___________________________

____

RUNNING EVENT(S) ____________________________________

BEST OFFICIAL TIME
FOR EVENT(S) ______________________

____

____

UNIVERSITY YEAR
OR GRADE ______________________

CLUB WITH WHOM
YOU TRAIN ____

PLEASE CHECK OFF THE TIMES WHEN YOU WOULD BE AVAILABLE FOR TESTING

MONDAY	MORNING	AFTERNOON
TUESDAY	MORNING	AFTERNOON
WEDNESDAY	MORNING	AFTERNOON
THURSDAY	MORNING	AFTERNOON
FRIDAY	MORNING	AFTERNOON
SATURDAY	MORNING	AFTERNOON
SUNDAY	MORNING	AFTERNOON

SUBJECT PROCEDURE FORM

Instructions Given to Subjects

1. You will run four - 100 yard sprints.

2. You are asked to run as fast as possible throughout the entire 100 yard distance.

3. Your time will be taken for the 100 yards.

4. Ten minutes recovery will be allotted between each run. If you need more time to rest between runs, this will pose no problem, as you may take as long as you like.

5. Before each run, you may warm up to a level that you consider adequate.

6. There will be two starting lines and two finish lines. The first and third run shall be made from starting line #1 and the second and fourth run shall be made from starting line #2.

7. A running approach shall be made beginning 5 yards from the normal starting line.

8. You will start at the command 'go', but you will be timed from the starting line at the flash of the pistol.

APPENDIX D

ANALYSIS OF VARIANCE

TABLE XVII

ANALYSIS OF VARIANCE FOR ANGLE OF UPPER BODY AT INITIAL CONTACT
(N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	50.5802	2	25.2901	1.1605
Within Groups	457.6433	21	21.7925	
Total	508.2234	23		

No significant differences between means at each velocity

TABLE XVIII

ANALYSIS OF VARIANCE FOR ANGLE OF UPPER LEG AT INITIAL CONTACT
(N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	461.8738	2	230.9369	8.4113 ***
Within Groups	576.5640	21	27.4554	
Total	1038.4377	23		

*** Significantly different at the .01 level

Significant differences using Newman Keuls (α =.01): maximum vs. slowest velocity

TABLE XIX

ANALYSIS OF VARIANCE FOR THE ANGLE OF THE LOWER LEG AT INITIAL CONTACT (N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	227.5735	2	113.7867	7.8826 ***
Within Groups	303.1387	21	14.4352	
Total	530.7122	23		

*** Significantly different at the .01 level

Significant differences using Newman Keuls (α =.01): maximum vs. intermediate velocity

TABLE XX

ANALYSIS OF VARIANCE FOR THE ANGLE OF THE FOOT AT INITIAL CONTACT (N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	8683.1250	2	4341.5625	0.8902
Within Groups	102417.0625	21	4877.0000	
Total	111100.1875	23		

No significant differences between means at each velocity

TABLE XXI

ANALYSIS OF VARIANCE FOR CONTACT TO CREST AT INITIAL CONTACT
(N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	116.5525	2	58.2762	5.4068 **
Within Groups	226.3463	21	10.7784	
Total	342.8987	23		

** Significantly different at the .05 level

Significant differences using Newman Keuls (α =.05): maximum vs. slowest velocity; intermediate vs. slowest velocity

TABLE XXII

ANALYSIS OF VARIANCE FOR CONTACT TO HIP AT INITIAL CONTACT
(N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	142.8609	2	71.4304	6.6182 ***
Within Groups	226.6528	21	10.7930	
Total	369.5137	23		

*** Significantly different at the .01 level

Significant differences using Newman Keuls (α =.01): maximum vs. slowest velocity; intermediate vs. slowest velocity

TABLE XXIII

ANALYSIS OF VARIANCE FOR ANGLE OF BODY LEAN AT EFFECTIVE CONTACT

(N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	129.7598	2	64.8799	5.1255 **
Within Groups	227.8474	18	12.6582	
Total	357.6072	20		

** Significantly different at the .05 level

Significant differences using Newman Keuls (α=.05): maximum vs. slowest velocity; intermediate vs. slowest velocity

TABLE XXIV

ANALYSIS OF VARIANCE FOR ANGLE OF UPPER LEG AT EFFECTIVE CONTACT

(N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	224.5052	2	112.2526	4.0097 **
Within Groups	503.9124	18	27.9951	
Total	728.4175	20		

** Significantly different at the .05 level

Significant differences using Newman Keuls (α=.05): maximum vs. slowest velocity

TABLE XXV

ANALYSIS OF VARIANCE FOR THE ANGLE OF THE FOOT AT EFFECTIVE CONTACT (N=7)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	48.3365	2	24.1683	1.8593
Within Groups	233.9772	18	12.9987	
Total	282.3137	20		

No significant differences between means at each velocity

TABLE XXVI

ANALYSIS OF VARIANCE FOR CONTACT TO CREST AT EFFECTIVE CONTACT (N=7)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	42.4443	2	21.2222	3.0326
Within Groups	125.9657	18	6.9981	
Total	168.4100	20		

No significant difference between means for each velocity

TABLE XXVII

ANALYSIS OF VARIANCE FOR CONTACT TO HIP AT EFFECTIVE CONTACT (N=7)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	55.2059	2	27.6029	3.7295 **
Within Groups	133.2239	18	7.4013	
Total	188.4298	20		

** Significantly different at the .05 level

Significant differences using the Newman Keuls (α =.05): maximum vs. slowest velocity

TABLE XXVIII

ANALYSIS OF VARIANCE FOR ANGLE OF BODY LEAN AT CENTER OF GRAVITY CONTACT (N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	289.6343	2	144.8171	3.4652 **
Within Groups	877.6335	21	41.7921	
Total	1167.2678	23		

** Significantly different at the .05 level

Significant differences using Newman Keuls (α =.05): maximum vs. slowest velocity

TABLE XXIX

ANALYSIS OF VARIANCE FOR ANGLE OF UPPER LEG AT CENTER OF GRAVITY CONTACT (N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	10.5478	2	5.2739	0.5052
Within Groups	219.2408	21	10.4400	
Total	229.7886	23		

No significant difference between means at each velocity

TABLE XXX

ANALYSIS OF VARIANCE FOR ANGLE OF LOWER LEG AT CENTER OF GRAVITY CONTACT (N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	15.8933	2	7.9467	0.3847
Within Groups	433.7678	21	20.6556	
Total	449.6611	23		

No significant difference between means at each velocity

TABLE XXXI

ANALYSIS OF VARIANCE FOR ANGLE OF THE FOOT AT CENTER OF GRAVITY CONTACT (N=8)

Source	Sum of Squares	DF	Mean Square	F-Ratio
Between Groups	159.2915	2	79.6458	1.4246
Within Groups	1174.0374	21	55.9065	
Total	1333.3289	23		

No significant difference between means at each velocity

VITA

D. Paul Roche

Date of Birth: August 8, 1947

Place of Birth: Cornwall, Ontario

Elementary Education: St. Mary's Separate School (Cornwall)

St. Columban's Boy's School (Cornwall)

Secondary Education: Cornwall Collegiate and Vocational Institute

University: Entered McMaster University and received Strathcona Trust Fund on entrance

Graduated from McMaster University in 1970 with a Bachelor of Arts in Sociology and a Bachelor of Physical Education

Attended the University of Windsor in Graduate Studies in the Faculty of Physical and Health Education from June,1970 to Septmeber, 1971

During the Graduate Program at Windsor, received assistanships in following areas:

1) Recreation

2) Biomechanics and Audio-Visual Aids