DOCUMENT RESUME

ED 040 482 24 CG 005 732

AUTHOR Nelson, Richard C.
TITLE A Study to Determine the Biomechanics of Running in Skilled Trackmen. Final Report.
INSTITUTION Pennsylvania State Univ., University Park.
SPONS AGENCY Office of Education (DHEW), Washington, D.C. Bureau of Research.
BUREAU NO BR-8-B-012
PUB DATE 11 Mar 70
GRANT OEG-0-8-003329-4285(010)
NOTE 116p.

EDRS PRICE EDRS Price MF-$0.50 HC-$5.90
DESCRIPTORS Athletes, Athletic Activities, College Students, Exercise (Physiology), Human Body, *Individual Characteristics, *Motor Reactions, *Physiology, *Running

ABSTRACT

The purpose of this study is to investigate the manner in which selected mechanical elements of the running stride are altered with accompanying variations in the speed of running and the slope upon which running occurs. Subjects, 16 intercollegiate runners, were marked at reference points of the body pertinent to this study and filmed twice running: (1) on a flat surface; (2) uphill; and (3) downhill. Within the limitations of this study, it is concluded that the biomechanics of the running stride are significantly altered by changes in speed, and the slope of the running surface. It is also apparent that the effects of slope and speed do not exercise a uniform influence upon individuals. (Author/KJ)

BR 8-B-012
PA 24

ED0 40482

Final Report

Project No. 8-B-012
Grant No. OEG-0-8-003329-4285(010)

A Study to Determine the Biomechanics of Running in Skilled Trackmen

Richard C. Nelson

The Pennsylvania State University

University Park, Pennsylvania

March 11, 1970

The research reported herein was performed pursuant to a grant with the Office of Education, U.S. Department of Health, Education, and Welfare. Contractors undertaking such projects under Government sponsorship are encouraged to express freely their professional judgment in the conduct of the project. Points of view or opinions stated do not, therefore, necessarily represent official Office of Education position or policy.

U.S. DEPARTMENT OF
HEALTH, EDUCATION, AND WELFARE

Office of Education
Bureau of Research

CG 005 732

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

In an age in which the capacity of science and its methods to investigate virtually all phenomena which lend themselves to quantification (measurement) remains virtually unquestioned, much controversy and misconception yet exists with regard to various mechanical aspects of the running stride. Much of the technology previously made available to other empirically-oriented disciplines has but recently been employed in the study of the mechanics of athletic movement. In the mid-twentieth century when the philosophical and biological, physical, and social scientific implications of athletics are so overwhelmingly great, an improved understanding of, and consensus concerning, its nature appears desirable.

The physiological mechanisms associated with explaining the stresses imposed by running upon the human organism have received considerable attention in the professional literature of the past five decades. Much less interest has been focused upon the mechanics of the running stride, however. And many of the conclusions which have been forthcoming conflict rather markedly with others. Indeed, many assertions have been couched in terms of opinion-like or analytically determined "fact," when actually they have been presented as empirically evolved conclusions. Few studies have concerned themselves with the collection, organization, analysis, and interpretation of empirical data.

Of the research which has been accomplished with regard to the mechanics of running, none has been concerned with the manner in which the mechanical components of the running stride are altered while running up and/or down slopes, and few have studied the alteration of stride mechanics which accompany variations of running tempos. The literature, then, requires either new assertions or support for those already existent. The implications of such findings for any runner required to alter his pace during the course of his performance, and most particularly for cross country runners who are frequently required to run either up or down slopes are obvious, and of considerable import.

I. THE PROBLEM

Purpose of the study. The purpose of this study has been to investigate the manner in which selected mechanical aspects of the running stride are altered with accompanying variations in the speed of run and the slope upon which the running occurred. The mechanical aspects of the running stride chosen for study were:

1. Stride length.
2. Stride rate (frequency).
3. Period of support.
4. Period of non-support.
5. Ratio of the period of support to period of non-support.
6. Horizontal distance of heel to hip at contact.
7. Vertical distance of height of body at contact to height of body at take-off.
8. Vertical distances of height of body at contact to height of body at temporal mid-non-support.
9. Body angle at contact to vertical.
10. Angle of the leg segment at contact to horizontal.
11. Angle of the leg segment at take-off to horizontal.
12. Angle of the driving thigh segment at take-off to vertical.
13. Body angle at take-off to vertical.
14. Foot contact data--the area of the plantar surface of the foot which establishes initial contact with the supporting surface.

Limitations of the study. The very nature of cinematography, as herein used, presupposes that movement occurs exclusively in one plane--that which is parallel to the camera lens. The running movements, while occurring primarily in the sagittal plane (in this case that which is parallel to the camera lens) are not limited to this plane alone. Indeed, movements in the transverse and coronal (frontal) planes were considerable, yet became manifest (with reference to the image imposed upon the film) only to the degree to which they distorted apparent movement in the sagittal plane. Some measurement error was, therefore, unavoidable.

Some discrepancies with reference to the runners' speed of movement did present themselves, since the runners were unable to precisely duplicate the pacer's rate of movement. Varying degrees of aberration between trials were apparent as a result of the foot under scrutiny having alighted at somewhat different points on the running surface. Also, since the plane of the running surface was not definitively marked, it became difficult to level the screen with reference to the running surface; so that, all angles could be measured with reference to the running surface. Suspect, as well, was the placement on the running togs of the marker at the hip joint; so that, it occasionally moved much too freely and inconsistently. Another factor which may have influenced the results of the investigation was that some of the runners were experienced cross country athletes, accustomed to running up and down hills, while others were experienced track performers who were untrained in the rudiments of hill running.

II. DEFINITION OF PERTINENT TERMS

The following terms are explained in accordance with their particular usage in this experiment:

Body angle. Body angle refers to the angle the trunk segment describes to vertical.

Driving thigh. The driving thigh refers to the swinging, non-supportive, thigh segment.

Foot contact data. Foot contact data refers to that which results from observations as to which portion of the plantar surface of the foot first alights on the running surface.

Period of non-support. The period of non-support refers to the time during which no part of the runner's body is in contact with the running surface.

Period of support. The period of support refers to the time during which one of the runner's feet, or a part thereof, is in contact with the running surface.

Stride length. Stride length refers to the horizontal distance traversed per stride.

Stride rate. Stride rate refers to the frequency with which the stride recurs.

Temporal mid-non-support. Temporal mid-non-support refers to the athlete's assumed position at the moment which, with reference to time, is midway between the instant at which one support phase is terminated and the subsequent one is initiated.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

Most of the available literature concerning the mechanics of running has been published in the popular coaching periodicals. And as is most commonly the case, the observations attributed to these "studies" are largely qualitative--empirically unverified--in character. In many of these sources it was difficult to determine the effect of earlier studies upon those more recently completed, as many assertions were rather poorly, or wholly not, documented. Far fewer studies of a quantitative and empirically acceptable nature have appeared in the professional research journals. Pertinent studies from each group--popular and professional--have been reviewed.

Only two studies encountered related directly to the problem of human locomotion up and/or down slopes. Gallnick and Karpovich (1964, p. 357), in their study involving hill walking, asserted that, "Changing the inclination of the walking surface produced alterations of the knee and ankle goniograms which were consistent with body mechanics necessary to adjust to the respective grades." Soule (1966) suggested that one must attempt to minimize the period of non-support except in hill running. These observations in themselves contribute little toward answering the questions posed by this investigation. They do imply, however, that hill running may differ in mechanical respects from running on a horizontal surface. Other studies have indicated the effect of alterations in the tempo of the run upon stride mechanics.

Selected Biomechanical Research

Literature concerning selected biomechanical components of the running stride has been arranged and presented in the following categories: stride length, stride rate, period of support, period of non-support, ratio of period of support to period of non-support, horizontal distance of heel to hip at contact, vertical movements of the body, body angles, angle of the lower leg segment at contact, angle of the lower leg segment at take-off, angle of driving thigh segment at take-off, and foot contact data.

Stride length. Weber and Weber (1836), Marey (1887), Demeny (1924), Fenn (1930), Cureton (1935), Bunn (1955), Wilt (1964), Cavagna, Margaria, and Arcelli (1965), Neuman (1966), Neuman (1967), and Cooper and Glassow (1968) all reported a positive relationship between stride length and the velocity of run. While Slater-Hammel (1939) and Dittmer (1962) noted that the fastest runners in their studies exhibited the longest strides. Beck's (1965) concern was with the alterations in the stride lengths of elementary school children in grade levels one through six. She concluded that mean stride length had increased from 98.8 inches in grade one to 131.1 inches in grade six. In his investigations at the University of Helsinki, Rompotti (1956) asserted, unlike all other researchers, that the velocity of run has no influence whatever upon stride length. The stride length, he suggests, of the same athlete in relaxed "half speed" is somewhat longer than that in full speed running.

Stride rate. Fenn (1929) concluded that an increase in running velocity is attained by increasing both the stride length and the stride rate. Slater-Hammel (1939) and Dittmer (1962) noted that the fastest runners in their studies had exhibited the highest stride frequencies. Cavagna, Margaria, and Arcelli (1965), Neuman (1966), Neuman (1967,a), Neuman (1967,b), and Cooper and Glassow (1968), in somewhat more general terms, asserted that a direct proportionality between velocity of movement and stride frequency exists. Cavagna (1965) qualified his similar observations by excluding the initial acceleration phases of running from them.

Period of support. Dittmer (1962), Cooper and Glassow (1963), and Neuman (1967,b) observed an inverse relationship between the duration of the support phase and the velocity of run. Hopper (1962) asserted that a sprinter spends but 40 per cent of the time required to complete a stride in support. Wilt (1964) concurred and noted that middle distance runners are in support 50 per cent of the time required to complete a stride. The conclusions of Hopper (1962) and Wilt (1964) appear, then, to be in agreement with others.

Period of non-support. Hopper (1964, p. 521) advocated attempting to suspend the runner "off the ground for the greatest possible time before the next ground contact." He offered no empirical evidence in support, however. Soule (1966) attested to the desirability of minimizing the period of non-support, except in hill running; while also noting that the period of non-support is proportionately less in middle distance running than in sprinting. He, then, supported the existence of a positive relationship between the velocity of run and the period of non-support, as have others. Again, no convincing evidence was included. Neuman (1967,a) empirically confirmed the validity of Soule's (1966) contentions by asserting that the duration of the non-support (floating) phase increases with increased velocity. The best sprinter in Neuman's (1967,a) study exhibited longer periods of non-support than had others. The results of this investigation were of very high statistical significance.

Ratio of period of support to period of non-support. With reference to developmental trends in runners, Dittmer (1962) found the relative duration of the non-support phase to increase, and, consequently that of the support phase to decrease with age and quite evidently with ability to perform well (to run at relatively high velocities). Beck (1965), in more highly quantified terms, noted the relative duration (in terms of percentages) of the non-support phase to increase from 45.3 in grade level one to 51.3 in grade level six alluding, then, to the same phenomenon as did Dittmer (1962). Housden (1964), having assumed the duration of the period of support to be one, concluded, after having observed a group of sprinters which included such luminaries as Dave Sime and Peter Radford, that the duration of the period of non-support was between 1.3 and 1.5. Neuman (1967,a), in a mechanical analysis of the running strides of 12-13 year old boys during the initial one to six strides from the starting blocks, contended that the period of support: period of non-support ratio approaches one from higher values as the velocity of run increases.

Horizontal distance of the heel to hip at contact. Since no segmental analysis of the body's center of gravity has been performed, the hip joint has been considered to be a reasonable approximation thereof. The literature would indicate this to be a legitimate assumption. Consequently, the horizontal distance between the center of gravity and the heel at contact, and that between the hip joint and the heel at contact both reflect a retarding effect upon the desired movement of the body. All references in the literature are to the center of gravity, however.

In a study of several sprinters, Fenn (1930) and Fenn (1931) indicated the point of foot contact to be in front of the body's center of gravity for approximately 0.03 seconds following track contact. Bunn (1955, p. 111) has, conversely, stated that the proper body angle "tends to keep the center of gravity ahead of the striding foot as it contacts the ground." The demeanor of Bunn's book alone, however, might suggest this to be a prescription of what is to be most desired in running technique, as opposed to a description of the manners in which men run. The morphologic limitations to which man is bound, therefore, have been disregarded. These appear to be reasonable observations in that no empirical evidence of any sort attended the remarks attributed to Bunn (1955). Contentions of a similar sort by Housden (1964), Wilt (1964), and Soule (1966) support those of Bunn while being contra those of all other investigators. Dittmer (1962) and Deshon and Nelson (1964) have indicated, however, that the total body mass moves more nearly over the foot at landing in the strides of accomplished runners, than it does in those of relatively inferior ability. Hopper (1962) in concurrence with most of the scientifically acceptable evidence has suggested that the immediate effect of track contact is to produce a thrust on the body well in front of the center of gravity. Dyson (1964), also in agreement, has noted that the distance which the foot lands in front of the center of gravity decreases as the velocity of run increases. And Beck (1965) discovered that the mean period of support devoted to propulsion increases from 54.3 per cent in grade one to 60.0 per cent in grade six. This may tend to indicate, as have others, that the horizontal distance between the foot at landing and the center of gravity decreases with increments in the ability to run more efficiently and more rapidly.

Vertical movements of the body. Fenn (1930) discovered that the entire body rises synchronously with the rise of the center of gravity within the body; a contention later supported by Kroll and Morenz (1931) and White (1966). Fenn (1930) also noted, as did White (1966), that this rise becomes maximal at the very termination of the period of support. Virtually all of the rise of the center of gravity within the body and that of the entire body itself, therefore, occurs during the period of support. Kroll and Morenz (1931) observed the paths of the curves described by the head, center of gravity, and hip to travel in very nearly parallel fashion one to the others in each of their three subjects. Despite Rapp's (1963) unique and perhaps questionable method of measuring body rise--it being the difference between the height of the toe of the trailing (swinging) foot as it passes directly (with reference to the vertical) over the heel of the supporting foot and that of both feet as they become equidistant from, and parallel to, the running surface--his conclusions may be of some value in that they do indicate a vertical displacement of some sort. He concluded that alterations in the velocity of run related inversely to the magnitude of body rise. The results were significant at the .001 level.

Body angles. Bunn (1955) and Soule (1966) have suggested, again without apparent support, the ideal body angle to be 20° from the vertical. Neither makes any reference to the possible relationship between body angle and velocity of run. Wilt (1964, p. 235) observed that, "Body angle at uniform speeds tends to be nearly erect." Wilt's (1959) previous statements and those of Slocum and Bowerman (1963), Tricker and Tricker (1967), and Cooper and Glassow (1968) support this contention. Chapman (1961) noted acceleration to be the major mechanical factor affecting body angle. Cooper and Glassow (1963), in agreement with others, maintained that Herb Elliot exhibited a rather constant trunk inclination, but that it was marginally in arrears of the vertical--approximately 93° to the ventral horizontal. The film from which these data were extracted, however, represented the closing meters of Elliot's 1960 Olympic 1500 meter victory and world record performance--a moment in which fatigue was paramount. Doherty (1963), without reference to acceleration and its effect upon body angle, simply stated that body angle increases with speed of movement.

Angle of the lower leg segment at contact. Fenn (1931) observed that in sprinting the lower leg segment describes an angle of 70°-80° to the track surface at the instant of contact. Rasch and Burke (1963, p. 407) in suggesting, among other things, that the angle in question increases with velocity, noted, "The greater the speed of running the less the amount of restraint caused by the contact of the foot of the swinging leg." Deshon and Nelson (1964) observed a statistically significant relationship ($p < .01$) between the velocity of run and the angle of the lower leg segment at contact. White (1966) reported the existence of a positive relationship between the angle under scrutiny and the velocity of run.

Angle of the lower leg segment at take-off. Bunn (1955) noted an inverse relationship between the velocity of run and the magnitude of the angle described by the supporting lower leg segment to the track as contact is terminated. Doherty (1963) attempted to quantify the relationship of the supporting lower leg segment to the track at the moment of departure by suggesting without apparent corroberation that a line from the driving (supporting) foot at the last point of contact through the center of gravity should describe an angle of 25° with the vertical in sprinting. Cavagna, Saibene, and Margaria (1964) studied athletes running at a constant velocity of 20 kilometers per hour and reported that the angle described by the lower leg segment to horizontal as it departs the track surface varies between 63°-72°. From an analytic viewpoint Tricker and Tricker (1967) have contended that the optimum angle of projection is necessarily low, since the force applied does not greatly exceed that required to overcome the vertical inertia of the body.

Angle of the driving thigh segment at take-off. Cureton (1935, p. 10) stated that, "The propelling force is made more effective by raising the knees high." Gibson

(1953), Bunn (1955), Wilt (1959), Wilt (1964), and Cooper and Glassow (1968) have all observed a positive relationship between the magnitude of the angle described by the driving (swinging) thigh segment to vertical as the supporting foot departs the track surface and the velocity of run. Cooper and Glassow (1963, pp. 151-152) in a study of the stride mechanics of Herb Elliot have simply noted that "the thighs . . . approach the front horizontal . . . through a range of 61°;" thus, supporting in an indirect sense the desirability of raising the knees reasonably high during this phase of the stride. In Fortney's (1963) study involving subjects aged 7-11 years, the older boys and superior runners more closely approached the horizontal with the thigh segment than did the others. Deshon and Nelson (1964) reported a statistically nonsignificant relationship between the velocity of run and the "mean angle of leg lift," despite their having concluded that a "high knee lift" characterized efficient running. With but two very talented subjects running at quite similar velocities, White (1966) observed that the slower of the two exhibited the larger angle. The relationships, however, were drawn from a comparison between subjects, as opposed to within subjects.

<u>Foot contact data</u>. Fenn (1930) observed that the heel area of the plantar surface of the foot establishes

initial contact with the supporting surface. Fenn's (1930) investigation which involved several sprinters suggested that the foot landed "flat" on some occasions even while running at maximum velocity. Only Glassow and Cooper (1963) among all sources reviewed concurred. In their study of Herb Elliot "full foot contact" was detected. They hypothesized, however, that variations in foot contact may accompany alterations in velocity of run.

All other studies reviewed were apparently in agreement with the conclusions of Nett's (1964) investigation, which is perhaps the most comprehensive yet completed. Gibson (1953), Bunn (1955), Wilt (1959), Doherty (1963), Rasch and Burke (1963), Dyson (1964), Wilt (1964), Soule (1966), Sylvia (1966), and White (1966) are among those having drawn similar conclusions. Nett (1964) placed a camera 20-30 cm above the track surface in order to photograph runners of international quality in competition at 64 frames per second. The results indicated that at the fastest tempos (100 meters--200 meters) the foot first alights on its lateral border, high on the ball. At 400 meters the foot first alights upon an area somewhat more proximal. At 800 meters the foot first alights on its lateral border within the metatarsal arch. The position of the foot as it alights while running at this tempo is virtually flat (essentially the entire plantar surface of the foot being exposed to the running surface at the moment of its landing). At 1500 meters and longer distances the foot alights on its lateral border at the arch between the heel and the metatarsus. Whatever area of the foot first encounters the running surface, the heel (proximal portion) of the foot's plantar surface subsequently contacts it as well regardless of the distance being run or the tempo at which it is being run. The area of the initial alighting base, in conclusion, then, increases as does the distance being run.

CHAPTER III

EXPERIMENTAL PROCEDURES

The procedures associated with this investigation are presented in terms of the subjects and experimental design, cinematographic procedures, film analysis, calculation of experimental variables, and statistical and computational procedures. All filming sessions were conducted in Recreation Building as depicted in Figure 1, page 20, on the campus of The Pennsylvania State University between October 24, 1967 and November 2, 1967. All analyses were completed subsequently in the Biomechanics Laboratory, The Pennsylvania State University.

Subjects and Experimental Design.

Subjects. The 16 highly skilled subjects chosen for this study were all members of the 1967 freshmen or varsity cross country and/or 1967-1968 freshmen or varsity indoor and outdoor track and field teams at The Pennsylvania State University. All were male, caucasian athletes of from 18 to 22 years of age, whose athletic specialties ranged from the sprinting to the long distance running events.

Experimental design. The experimental conditions as depicted in Figure 2, page 21, consisted of twice running 1) on a flat (horizontal) surface, 2) uphill on a 10 per cent

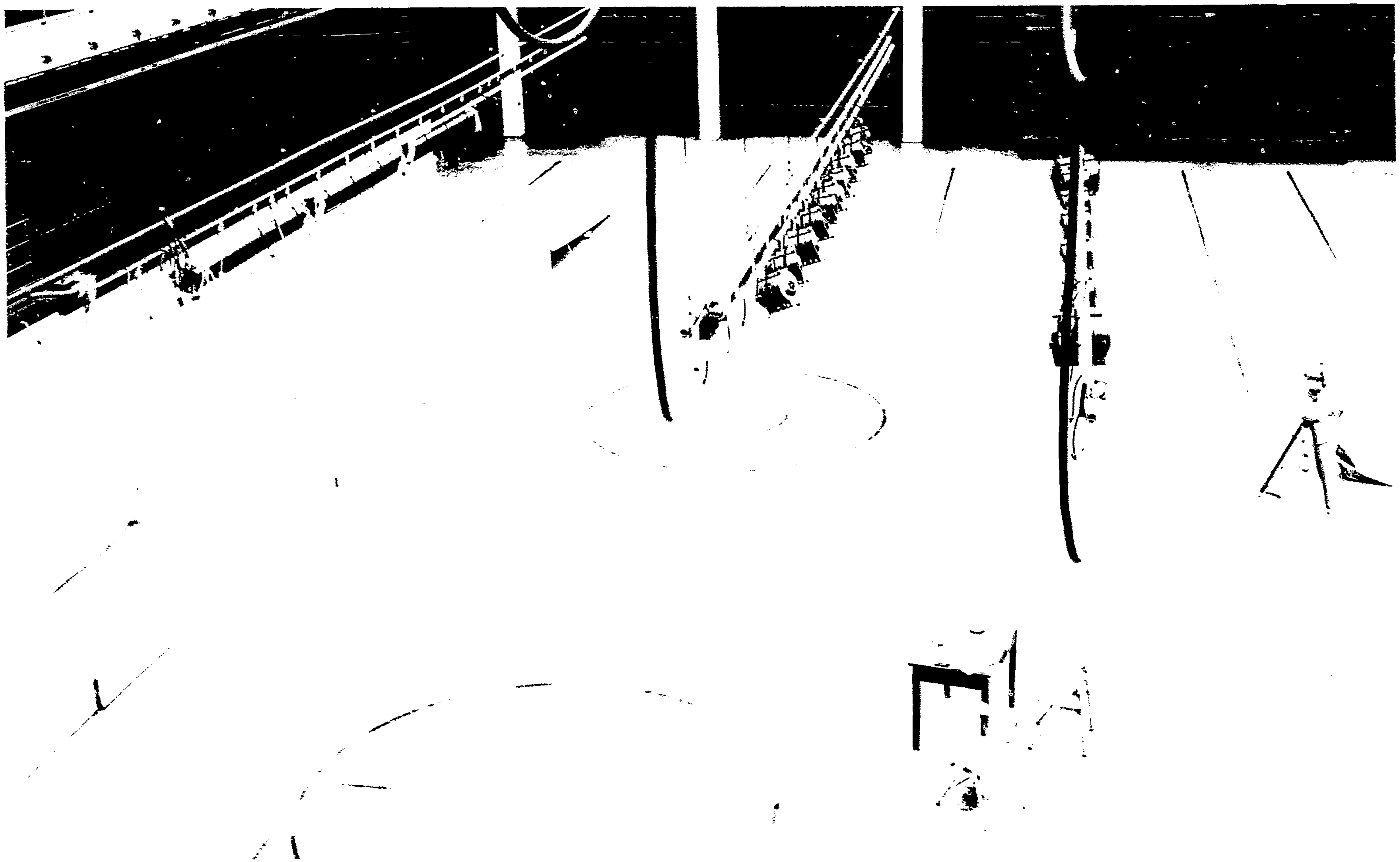

Figure 1. General Test Area.

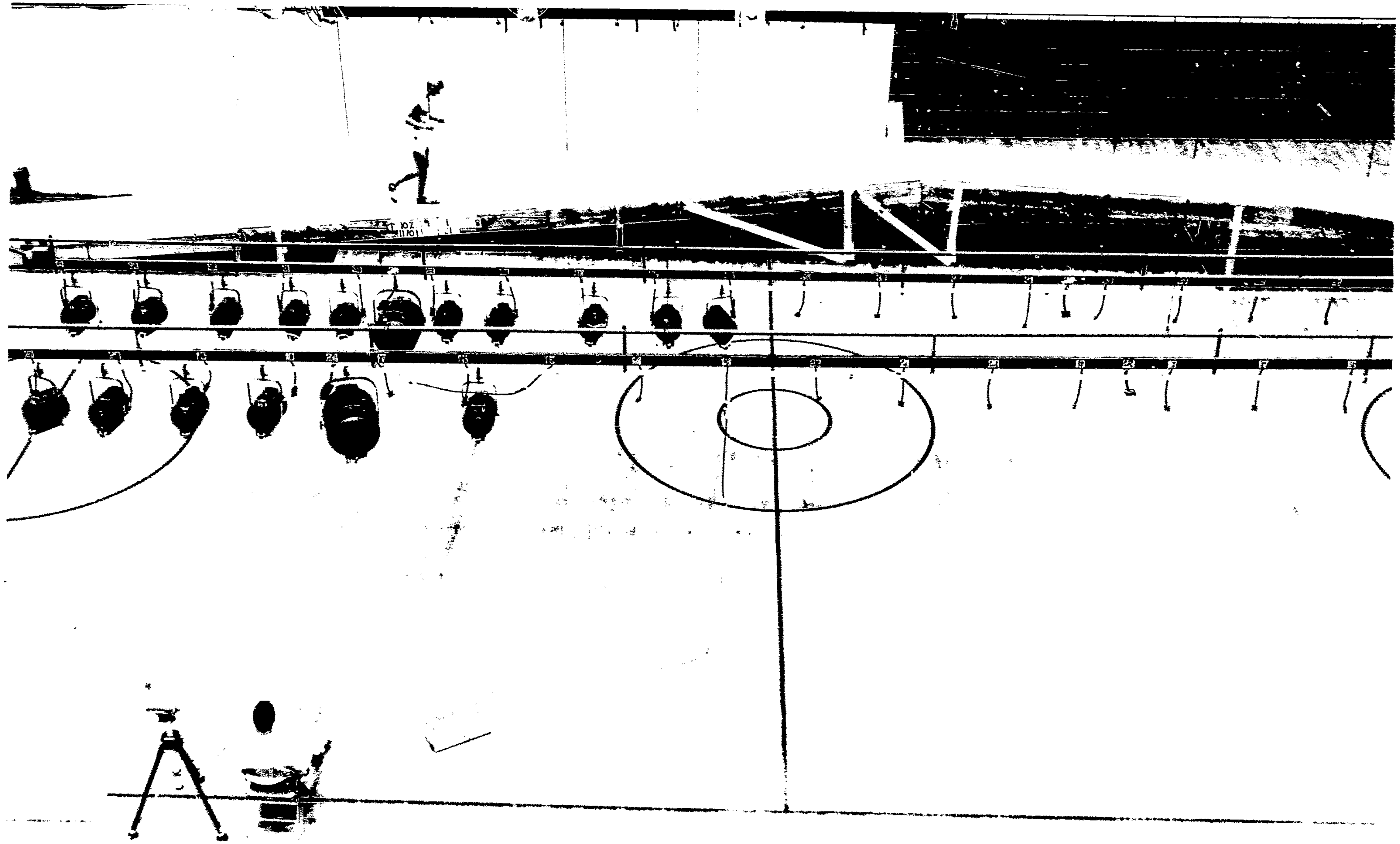

Figure 2. Test Condition.

slope, and 3) downhill on a 10 per cent slope at constant velocities (a = 0) of 11, 16, and 21 feet/second. These velocities if averaged over a 100-yard distance would produce respective times of 27.3, 18.8, and 14.3 seconds--all very slow indeed. These velocities and slopes were chosen because it was noted by observation that they appeared to be sufficiently dissimilar to effect detectable variations in stride mechanics. The velocities were controlled with the use of a pacing device which moved beside the runner at the desired velocity.

The trial sequence for each athlete was composed of one trial of each of the three velocital conditions on the first day scheduled for his horizontal trials, and the second trial of each of the three conditions on the second day. On the first day scheduled for his hill trials, all velocital conditions, both up and down slope, were filmed. On the second day scheduled for his hill trials this procedure was replicated. Each athlete was, therefore, required to perform on four separate, yet not necessarily consecutive, days. The conditions were always filmed in the 11-16-21 sequence. A "run-in" into the photographic field of several strides was required; so that, the athlete was running at a constant velocity when filmed.

Preceeding each trial, warm-up runs of 1-2 times the length of the runway were required. These were followed by two runs under filming conditions, which were subsequently followed by the filmed run itself. The athletes were told that all three trials were to be filmed while only the third of the three actually was. This permitted the runners to adequately acquaint themselves with the conditions of the trial, and permitted the investigator to use only that film which was essential to the investigation.

Cinematographic Procedures

Photographic and analytic equipment. A Hycam camera, Dupont Reversal Film 932-A, and Millimite camera speed calibration device were used in the filming of the runners in this study. A Vanguard Motion Analyzer, Model C-11D, was used in extracting data from the filmed images.

Preliminary taping. The body reference points pertinent to this investigation were marked with one-half inch square pieces of dark-colored tape; so that, they might be easily identified on the filmed images. The tape was, consequently, placed at the following points:

1. Behind the near ear (over the mastoid process).
2. Over the midpoint of the near hip joint (over the greater trochanter of femur).
3. Upon the lateral aspect of the near knee joint (over the articulation between the lateral condyle of femur and the lateral condyle of tibia), ankle joint (over the lateral malleolus of fibula), and along the plantar surface of the foot.
4. Upon the medial aspect of the far knee joint (over the articulation between the medial condyle of femur and the medial condyle of tibia), ankle joint (over the medial malleolus of tibia), and along the plantar surface of the foot.

Photographic procedures. The camera lens was placed at right angles to the running surface; so that it was located approximately at the level of the hips of the runner being photographed. It was placed some 35 feet 8 inches from the center of the running surface (from the nearest point on the runway perpendicular to the camera lens). Therefore the image of the entire runner was exposed to the film for an adequate period of time. The camera was not moved throughout the filming process. The f-stop at 5.6 admitted the proper amount of light to the film, and the camera speed of 160 frames per second permitted satisfactory distinction of critical points in the stride sequence. The record board in the photographic field indicated the film roll number, date, trial number, subject number, speed of run, and slope upon which the run occurred. The camera was started immediately before the runner entered the photographic field to insure proper camera speed throughout the four or five complete running strides filmed per trial. The yardstick, used for computation of the multiplier, was filmed at the beginning of each of the nine rolls of film.

Film Analysis.

The data extracted from the film may be considered as that which is intended to yield information regarding five different types of mechanical phenomena. The phenomena associated with the collection of data are those of horizontal displacement (in terms of x-coordinates), vertical displacement (in terms of y-coordinates), time periods (in terms of frames of duration), angles at critical points in the running movement, and foot contact (expressed in largely descriptive terms).

The viewing screen was adjusted so that all measurements, regardless of the slope upon which the movement had occurred, were made with reference to that running surface as opposed to a horizontal surface. The screen was adjusted, then, so that the running surface appeared horizontal even when it was not. This permitted all measurements to be made with reference to only one condition (the running surface), thus enhancing the clarity of the data, and precluding its further manipulation.

All measurements were extracted from an image which was as near to the center of the screen as possible, as the image at this point was somewhat more highly defined than elsewhere on the film, as a result of the light intensity being greater at this point. A left foot contact-take-off was analyzed in all horizontal and uphill trials, and a right foot contact-take-off was analyzed in all downhill trials. The direction of run changed between these trials since all trials were run over the same surface. The angles were, therefore, more easily and accurately extracted, as the position of the tape marking at the hip joint at no time had to be estimated. All measurements were once replicated, the mean of the two being accepted for analysis. Extracted angles and coordinates were rounded to two significant decimal places in standard fashion. Other measurements were rounded from a higher number of decimal places to the form in which they are presented also in standard fashion.

Horizontal displacement. The data associated with expressing horizontal displacement included the x-coordinates of the two ends of the yardstick, which was extracted once from each roll and was to be subsequently used in the computation of the multiplier, the x-coordinates of the heels at two consecutive points of contact which was extracted once per trial and was to be subsequently used in the computation of stride length, and the x-coordinate of the hip at contact which was extracted once per trial and was to be subsequently used in the computation of the horizontal distance of the heel to hip at contact.

The multiplier as a unitless expression of relationship between the dimensions of real objects and those of projected images on film is presented in terms of a ratio between the two (real/projected). The projected dimension was represented by the difference between the x-coordinates of the two ends of the yardstick, and the real dimension by the length of the yardstick itself (36 inches). The multiplier was computed, then, as the quotient of the two: $36/x-x_1$ since the attempt was to convert the dimensions of projected images to those of real objects.

Vertical Displacement. The data associated with expressing vertical displacement included the y-coordinates of the topmost portion of the head at contact, take-off, and temporal mid-non-support. These quantities were then to be subsequently used in the computation of the vertical distance of the height of the body at contact to the height of the body at take-off and of the vertical distance of the height of the body at contact to the height of the body at temporal mid-non-support.

The position at temporal mid-non-support was determined by counting back one-half the number of frames having been counted for the period of non-support from the second noted point of contact. In all instances wherein the number of frames counted for the period of non-support were uneven (odd) the countback was advanced to the next highest value (Example 21/2 = 11). This point, then, may not be spatially mid-like--it may not represent the highest point of the symmetric parabola, since the head may not be at the same height at both contact and take-off, and it may not be horizontally equidistant from the point of contact and that of take-off at the moments these points are established.

Time periods. The data associated with expressing time periods included the number of frames involved in the duration of the periods of support and non-support, each of which was extracted by merely counting them once per trial and was to be subsequently used in the computation of the periods of support and non-support themselves, the duration of the entire stride, and the stride rate. Since the calibration device deposited a white dot beside the exposed film every 1/100th of a second, it was possible to perform a frame rate count by simply counting the number of frames minus the first (as it is time segments, not actual numbers of frames with which one is concerned) which had accompanied the appearance of thirty white dots. The frame rate count was computed subsequently by equating a ratio of known quantity (30 dots/frames per 30 dots) to one of unknown quantity (100 dots per second/x frames per second). In solving the equation the frame rate count (x) is yielded in terms of frames per second. This procedure was performed twice on each roll of film.

Angles. The data associated with expressing angles at critical points in the running stride were extracted directly from the film, therefore, requiring no additional manipulation. Each angle of the following five was extracted once per trial: body angle at contact to vertical, angle of the lower leg segment at contact to horizontal, angle of the lower leg segment at take-off to horizontal, angle of the driving thigh segment at take-off to vertical, and body angle at take-off to vertical. The body angles were defined by the intersection of a cursor line connecting the tape marking on the near hip to the tape marking behind the near ear with a vertical line (perpendicular to the supporting surface). The angles of the lower leg segment at contact and take-off to horizontal were defined by the intersection of a cursor line connecting the tape marking at the knee joint to that at the ankle joint with a horizontal line (parallel to the supporting surface). And the angle of the driving thigh segment at take-off to vertical was defined by the intersection of a cursor line connecting the tape marking at the near knee joint to that at the near hip joint with a vertical line. The segments involved were very nearly bisected by this method.

Foot contact. The foot contact data, likewise, were extracted directly from the film, therefore, requiring no additional manipulation. As has been previously noted, the extraction of these data involved an attempt to observe which area of the plantar surface of the foot first established contact with the supporting surface. This observation was performed once per trial.

Calculation of Experimental Variables

As has been previously noted the five angles under scrutiny and the foot contact data required no additional treatment in order to render them analyzable. All other extracted elements of data (from film) did, however, demand modification. It is of pertinence, then, to articulate the terms of these modifications.

Horizontal displacement. The stride length was computed by applying the multiplier to the difference between the x-coordinates of the heels of two consecutive points of contact: multiplier $X(x-x_1)$. The horizontal distance of heel to hip at contact was computed by applying the multiplier to the difference between the x-coordinate of the heel at contact and that of the tape marking at the hip joint also at contact: multiplier $X(x-x_1)$. All computations associated with horizontal displacement were expressed in terms of inches.

Vertical displacement. The vertical distance of the height of the body at contact to the height of the body at take-off was computed by applying the multiplier to the difference between the y-coordinates of the topmost portion of the head at contact and that at take-off: multiplier $X(y-y_1)$. The vertical distance of the height of the body at contact to the height of the body at temporal mid-non-support was computed by applying the multiplier to the difference between the y-coordinates of the topmost portion of the head at contact and that at temporal mid-non-support: multiplier $X(y-y_1)$. All computations associated with vertical displacement were expressed in terms of inches.

Time periods. The duration of the period of support was computed in terms of seconds per support phase by determining the value of the quotient: number of frames per support phase/frames per second (frame rate). The duration of the period of non-support was computed in terms of seconds per non-support phase by, likewise, determining the value of the quotient: number of frames per non-support phase/frames per second (frame rate). The ratio of the period of support to period of non-support was, of course, computed by determining the quantity of that ratio, and is a unitless measure. The duration of the entire stride was computed in terms of seconds per stride by determining the value of the quotient: number of frames per stride/frames per second (frame rate). It could more easily have been computed by simply summing the durations of the periods of support and non-support, but the probability of markedly compounding rounding errors discouraged the use of this technique. The reciprocal of the duration of the entire stride represents the stride rate, which was subsequently expressed in terms of strides per second.

Velocity of run. The velocity of run was computed by determining the product of stride rate in terms of strides per second and stride length in terms of inches. The velocity of run was, therefore, expressed in terms of inches per second. The result of this aspect of the investigation, which was pursued no further, since it was of necessity considered to be a constant, indicated that in virtually all instances the athlete was able to closely, yet not precisely, reproduce the velocity of the pacing device.

Statistical and Computational Procedures

The importance of selecting the most satisfactory statistical procedures for data analysis is well noted by Nelson and Morehouse (1966, p. 441), "The accuracy of conclusions based on experimental research is dependent upon the use of appropriate statistical procedures . . ." Nelson and Morehouse (1966, p. 442) also indicate the procedure most applicable to multiple-group experiments: "The procedure usually recommended for comparing three or more groups is the analysis of variance."

The analysis of variance procedure involves the calculation of the quotient produced as a result of dividing the mean squares (variance estimates) of two groups of data by one another, and the determination via a one-tailed test (F-distribution) of the magnitude to which this ratio (F-ratio) differs significantly from one. This technique is well described by Winer (1962, pp. 278-9).

Of the 14 mechanical elements of the running stride of pertinence to this investigation, 13 were measured in terms of ratio scale values and lend themselves to treatment by computer programming techniques. Only the foot contact data, which were measured in terms of nominal scale values, were not suited to this sort of treatment. No statistical processes were, therefore, imposed, as these data were analyzed by merely organizing them and observing the patterns of movement involved.

Southern Illinois University (1968, p. 2) indicates that, "FORTRAN IV ANOVR is a general purpose analysis of variance routine which will handle factorial designs involving up to eight variables or factors. The program will accept designs with up to four Independent variables, A, B, C, and D, and up to four Repeated Measure variables, J, K, L, and M." This routine was designed by Southern Illinois University and is currently being used at the Computation Center, The Pennsylvania State University, where all of the programming required for this study was completed in July, 1968. The input data consisted of all measurement-calculations per mechanical element of the running stride (288) for each of these 13 elements as prescribed by the design of the program.

Nelson and Morehouse (1966, p. 441-2) have suggested that, "If the F-ratio indicates that differences among the groups are not significant, no further comparison of the groups is usually warranted," and, "when the F-ratio indicates a significant difference between groups, it is usually desirable to ascertain which of the groups differ significantly." In order to indicate, then, which of the groups differ significantly, Nelson and Morehouse (1966, p. 444) have preferred the use of the Tukey HSD test. Winer (1962, p. 89) maintains that the Tukey test is adequately conservative (yields few significant results), and that since it "is applicable in a relatively broad class of situations, and is simple to apply there is much to recommend it for general use in making a posteriori tests." The Tukey procedure as recommended by Snedecor (1956, p. 251) has been employed herein.

Since the central interest of this investigation has been the effect of speed and slope upon running mechanics the group means as to slope (3) were all treated as one set, as were the group means as to speed (3). Three differences per set per condition (stride length, stride rate, etc.) were, therefore, calculated in an attempt to ascertain which differences between groups were producing the variation noted by the analysis of variance, and to determine in which direction the variation occurred. The differences were rendered significant at the .01 or .05 level, then, if they exceeded the d-value at each of these respective levels.

CHAPTER IV

RESULTS

The results of this investigation are presented in terms of the effects of slope, speed and individual (and their interactions) upon the mechanical aspects of the running stride chosen for study. To simplify presentation of the results, interpretive statements are included in the discussion of each variable. The analysis is generated from the tables in the appendices, which present data from the analysis of variance procedures, Appendix A, and the Tukey tests, Appendix B. Since no pooling of variance estimates was required, the error estimate of variance became the denominator for the calculation of all F-ratios.

Stride Length

The results of the analysis of variance indicated that the variation of stride length due to the main effects (slope, speed, and individual) and the two-way interactions (slope x speed, slope s individual, speed x individual) was highly significant ($p < .01$). Further comparison of means via the Tukey tests indicated that the three differences between slope group means were statistically significant (horizontal-uphill, $p < .01$; horizontal-downhill, $p < .05$; and uphill-downhill, $p < .01$). The differences between stride lengths produced upon all three slopes, therefore, contribute significantly to the variation noted in the main effect of slope. These group means also showed that the mean stride length while running on a horizontal slope was greater than that produced on the uphill slope, but less than that exhibited while running on the downhill slope. The mean stride length produced on the uphill slope was, therefore, considerably less than that produced on the downhill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between stride lengths produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean stride length produced at 11 feet/second was considerably less than that produced at both 16 feet/second and 21 feet/second, and that the mean stride length at 16 feet/second was considerably less than that at 21 feet/second.

Figure 3, page 37, depicting the group means for stride length, indicates that the group means increased within each of the three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the downhill variable elicited the largest values, the horizontal trials somewhat lesser values, and the uphill condition the lowest values at each of the three speeds.

Within the conditions and limitations of this investigation, its results suggest that the variables of slope,

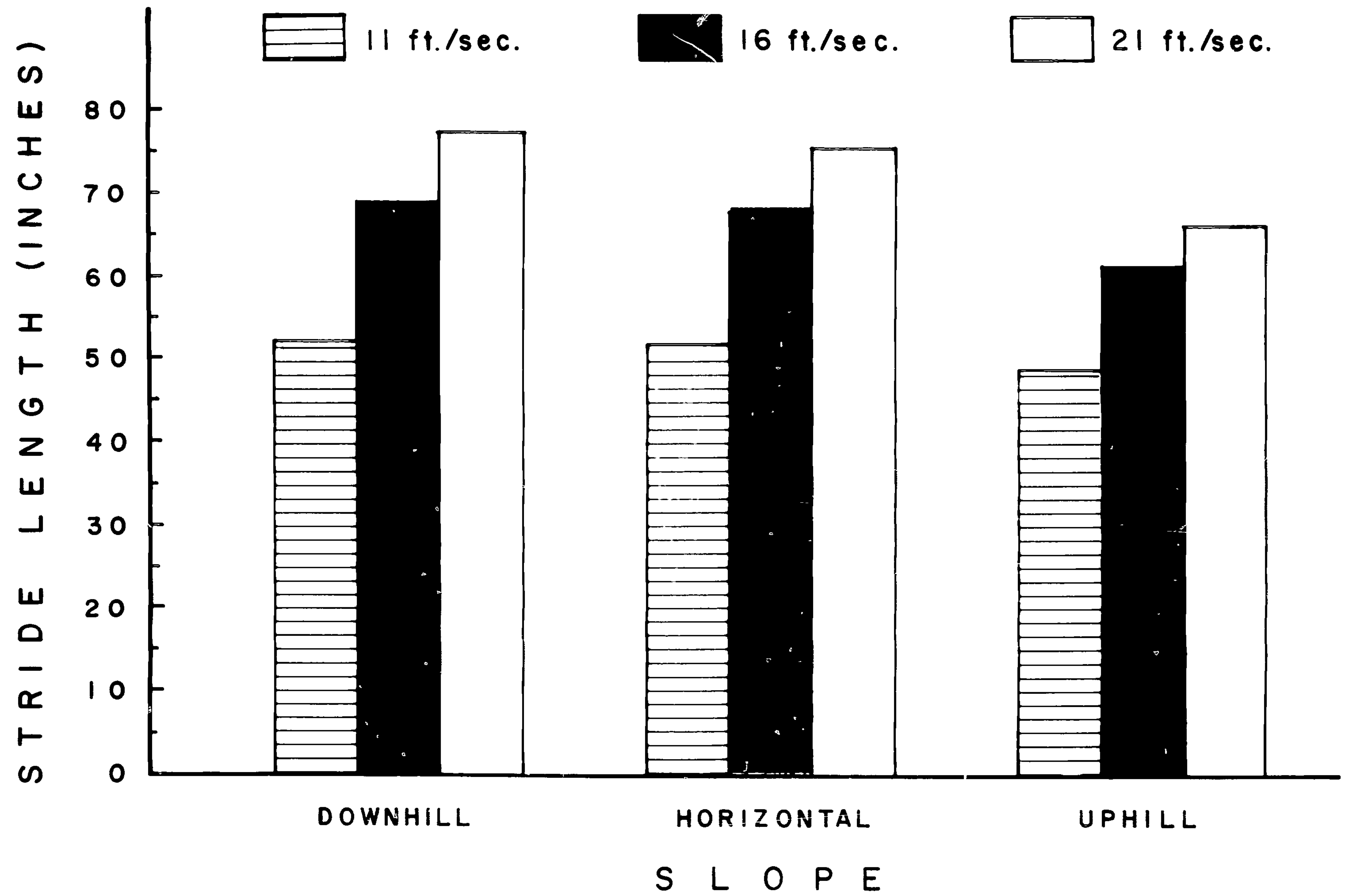

Figure 3. Group means for stride length within slopes and across speeds. (Performed overground)

speed, and individual exercised a considerable influence upon stride length. That is, as the speed of run increased or decreased, stride length did so accordingly, and as the slope became more or less severe (resistive to movement), the stride length shortened or lengthened in respective accordance. The results of the investigation regarding the relationship of speed of run to stride length follow well the results of all other reviewed research, except that of Rompotti (1956).

Stride Rate

The results of the analysis of variance revealed that the variation of stride rate due to the main effects (slope, speed, and individual), and the two-way interactions (slope x speed, slope x individual, speed x individual) was highly significant ($p < .01$). Evaluation of mean differences via the Tukey tests indicated that the three differences between slope group means were also highly significant ($p < .01$). The differences between stride rates produced upon all three slopes, therefore, contribute significantly to the variation noted in the main effect of slope. These group means also indicated that the mean stride rate while running on a horizontal slope was less than that produced on the uphill slope, but more than that exhibited while running on the downhill slope. The mean stride rate produced on the uphill slope was, therefore, greater than that produced on the downhill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between stride rates produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean stride rate produced at 11 feet/second was considerably less than that produced at both 16 feet/second and 21 feet/second, and that the mean stride rate at 16 feet/second was considerably less than that at 21 feet/second.

Depicting the group means for stride rate, Figure 4, page 40, indicates that the group means increased within each of the three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the uphill variable elicited the largest values, the horizontal trials somewhat lesser values, and the downhill condition the lowest values at each of the three speeds.

The results of this investigation, consequently, suggest that the variables of slope, speed, and individual exercised a considerable influence upon stride rate. That is, the stride rate increased as did speed of run, and decreased as the slope became less severe (resistive to movement). Therefore, within the limitations of this study, the results regarding the relationship of speed of run to stride rate follow well the results of all other reviewed research.

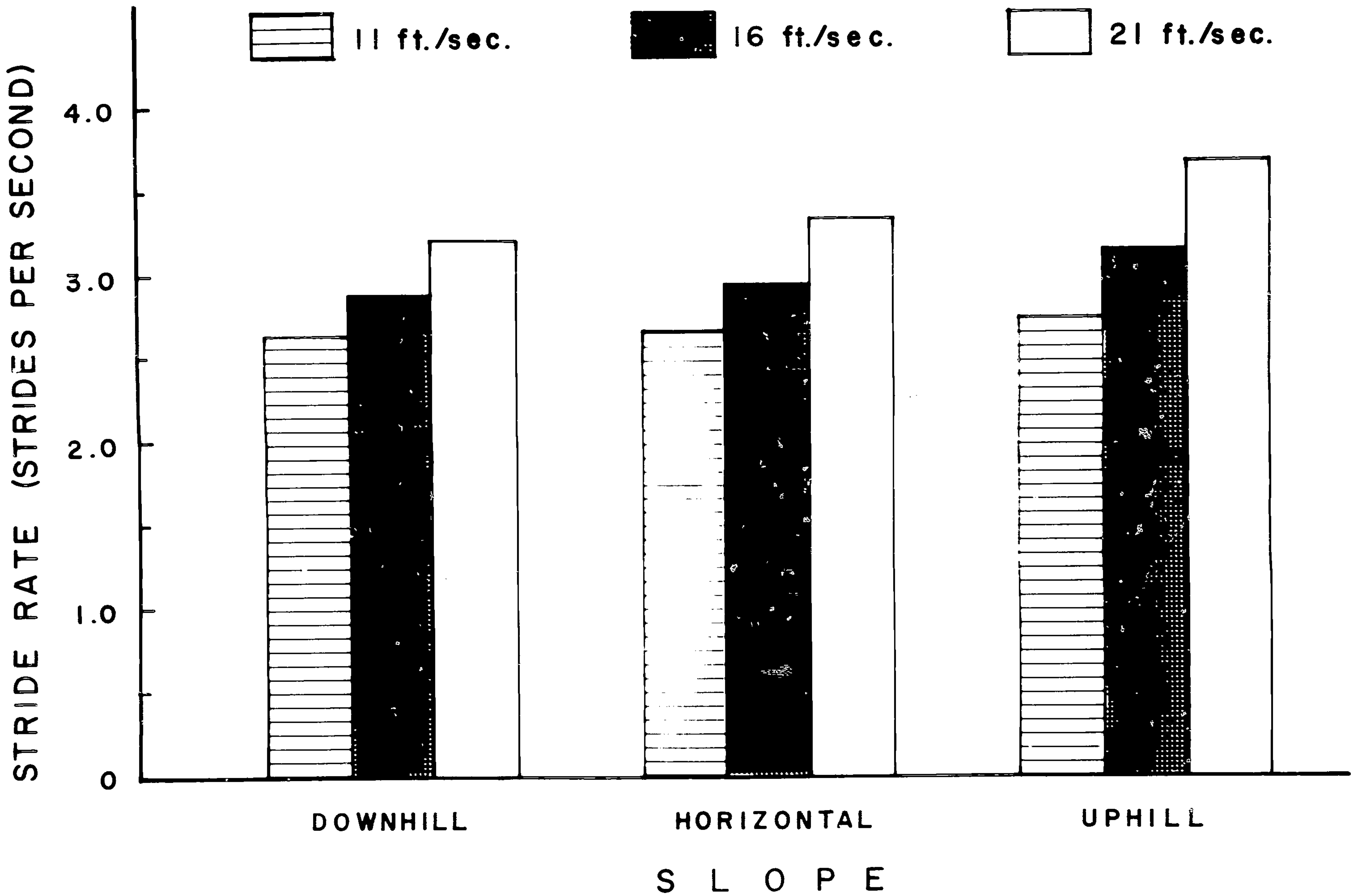

Figure 4. Group means for stride rate within slopes and across speeds. (Performed overground)

Period of Support

The results of the analysis of variance indicated that the variation of the period of support due to the main effects (slope, speed, and individual) and two of the interactions (slope x individual, and speed x individual) was highly significant ($p < .01$).

Further comparison of means via the Tukey tests revealed that two of the three differences between slope group means (horizontal-uphill and uphill-downhill) were highly significant ($p < .01$). The differences between periods of support produced upon these slopes as juxtaposed, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also indicated that the mean period of support while running on a horizontal slope was greater (longer) than that produced on either the uphill or downhill slope, and that exhibited on the downhill slope was greater than that produced on the uphill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between stride rates produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note was that the mean period of support produced at 11 feet/second was greater than that produced at either 16 feet/second or 21 feet/second, and that the mean period of support at 16 feet/second was considerably greater than that at 21 feet/second.

Figure 5, page 43, depicting the group means for the period of support, indicates that the group means decreased within each of the three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the horizontal variable elicited the largest values, the downhill trials somewhat lesser values, and the uphill condition the lowest values at both 11 feet/second and 16 feet/second. At 21 feet/second the downhill variable produced the largest values, the downhill trials somewhat lesser values, and the uphill condition the lowest values.

The results of this investigation, within its conditions and limitations, consequently, suggest that the variables of slope, speed, and individual exercised a considerable influence upon the period of support. That is, the period of support decreased as the speed of run increased; and very generally, it decreased from horizontal, to downhill, to uphill slopes. Therefore, the results of this study regarding the relationship of speed of run to period of support follow well the results of all other reviewed research.

Period of Non-support

The results of the analysis of variance revealed that the variation of the period of non-support due to the main effects (slope, speed, individual) and two of the interactions (slope x speed and slope x individual) was highly significant ($p < .01$). Examination of mean

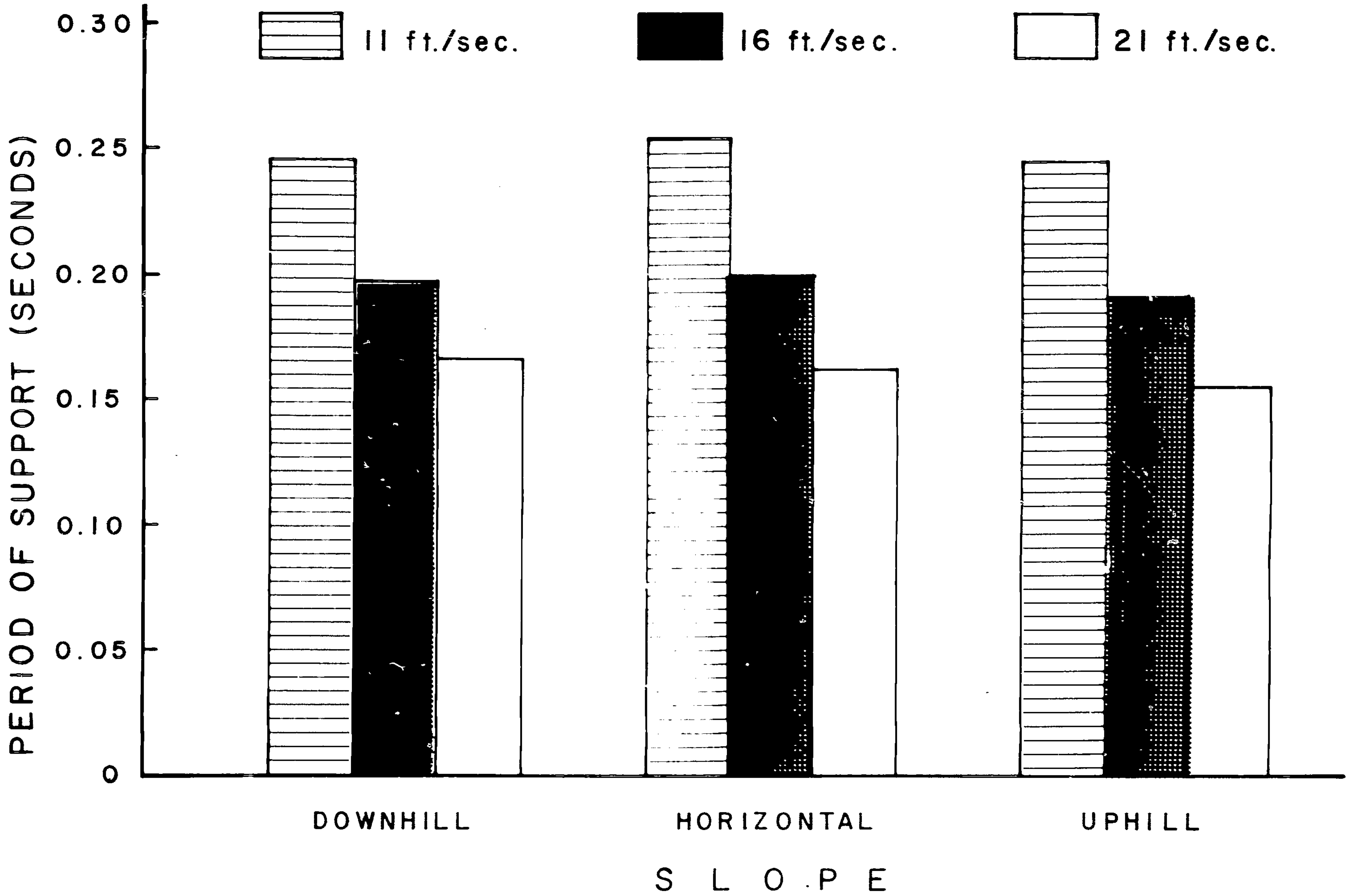

Figure 5. Group means for period of support within slopes and across speeds. (Performed overground)

differences via the Tukey tests indicated that the three differences between slope group means were highly significant ($p < .01$). The differences between periods of non-support produced upon all three slopes, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also revealed that the mean period of non-support while running on a horizontal slope was greater than that produced on the uphill slope, but less than that produced while running on the downhill slope. The mean period of non-support produced on the uphill slope was, therefore, considerably less than that exhibited on the downhill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between periods of non-support produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean period of non-support produced at 11 feet/second was considerably less than that produced at either 16 feet/second or 21 feet/second, and that the mean period of non-support produced at 16 feet/second was considerably greater than that at 21 feet/second.

Figure 6, page 45, depicting the group means for the period of non-support, indicates that the group means increased from 11 feet/second to 16 feet/second, but decreased from 16 feet/second to 21 feet/second within each of

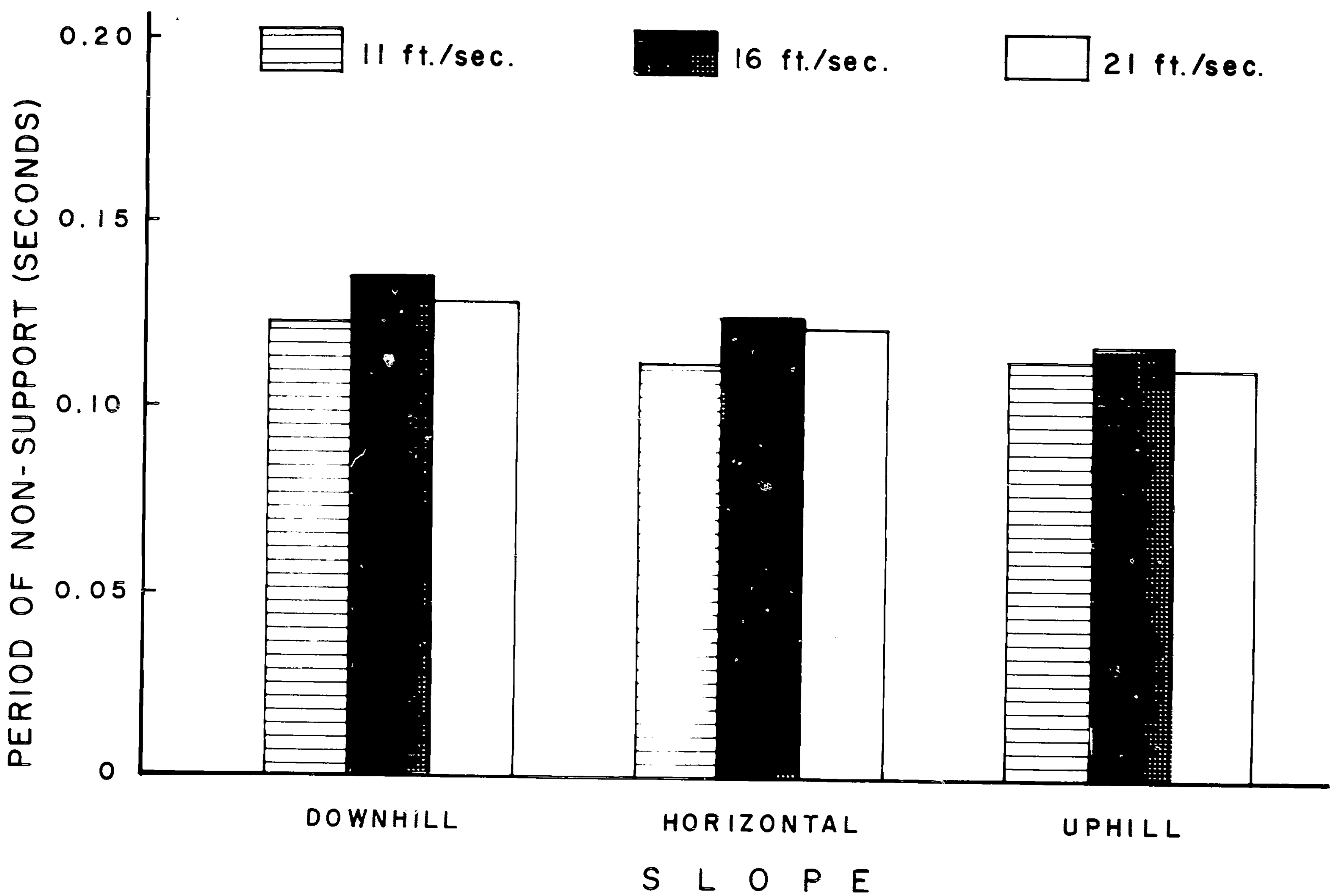

Figure 6. Group means for period of non-support within slopes and across speeds. (Performed overground)

the slopes. The values at 21 feet/second were greater than those at 11 feet/second in horizontal and downhill trials, but less in uphill trials. Across slopes, within speeds, these graphs suggest that the uphill variable elicited the largest values at each of the three speeds. At 11 feet/second the uphill condition produced somewhat lesser values and the horizontal trials the lowest values. At 16 feet/second and 21 feet/second, however, the horizontal condition produced somewhat lesser values and the uphill trials the lowest values.

The results of this investigation, consequently, suggest that the variables of slope, speed, and individual exercised a considerable influence upon the period of non-support. That is, the period of non-support increased as the speed of run increased to a given point only, then commenced to decrease; and very generally it decreased from downhill, to horizontal, to uphill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run and slope to period of non-support support many of the results of the reviewed literature. Without reference to the speed of run, Hopper (1964) and Soule (1966) attested to the absolute desirability of increasing and decreasing the period of non-support, respectively. Neuman (1967) maintained that the period of non-support is positively (directly) affected by alterations in the speed of run. He observed only the first six strides from the blocks, however--a period in which the velocity is not constant. Within the conditions and limitations of this study, the results refute the validity of any statement which fails to refer to the altering character of the relationship in question (speed of run to period of non-support) at divergent speeds of run.

<u>Ratio of Period of Support to Period of Non-support</u>

The results of the analysis of variance indicated that the variation of the ratio of period of support to period of non-support due to the main effects (slope, speed, and individual) and the two-way interactions (slope x speed, slope x individual, speed x individual) was highly significant ($p < .01$). Further comparison of means via the Tukey tests revealed that two of the three differences between slope group means (horizontal-downhill and uphill-downhill) were highly significant ($p < .01$). The differences between the ratio of periods of support to periods of non-support produced upon these slopes as juxtaposed, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also note the mean ratio of period of support to period of non-support while running on a horizontal slope to be less than that produced on the uphill slope, but more than that exhibited while running on the downhill slope. The mean ratio of period of support to period of non-support produced on the uphill slope was, therefore, greater than that produced on the downhill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between ratios of periods of support to periods of non-support produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean ratio of period of support to period of non-support produced at 11 feet/second was considerably greater than that exhibited at either 16 feet/second or 21 feet/second, and that the mean ratio of period of support to period of non-support at 16 feet/second was considerably greater than that at 21 feet/second.

Depicting the group means for the ratio of period of support to period of non-support, Figure 7, page 49, indicates that the group means decreased within each of the three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the horizontal variable elicited the largest values, the uphill trials somewhat lesser values, and the downhill condition the lowest values at 11 feet/second. At 16 feet/second and 21 feet/second the uphill variable produced the largest values, the horizontal trials somewhat lesser values, and the downhill condition the lowest values.

The results of this investigation, consequently, suggest that the variables of slope, speed, and individual

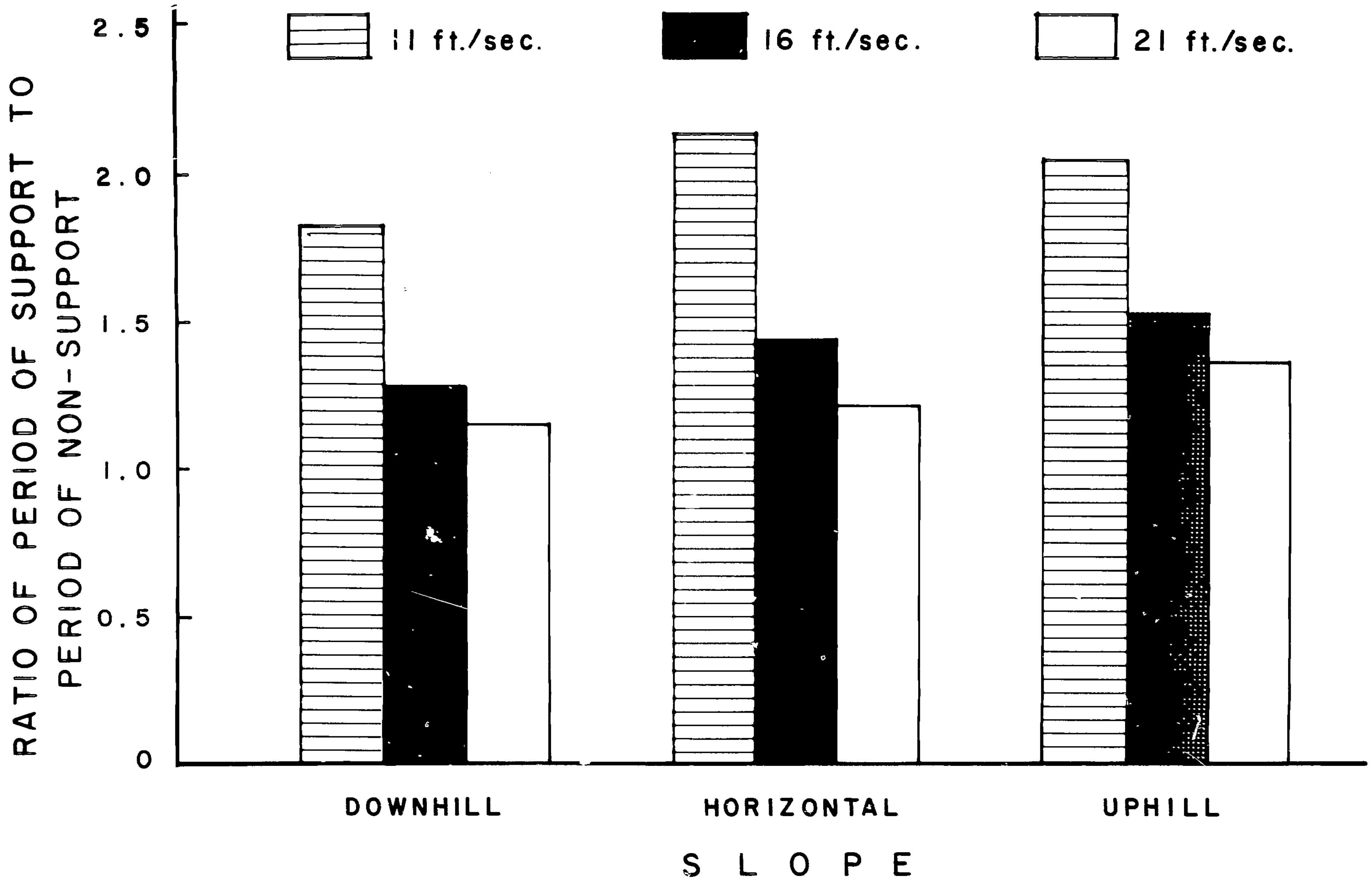

Figure 7. Group means for ratio of period of support to period of non-support within slopes and across speeds. (Performed over-ground)

exercised a considerable influence upon the ratio of period of support to period of non-support. That is, the ratio of period of support to period of non-support decreased as the speed of run increased; and very generally, it decreased from uphill, to horizontal, to downhill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run to the ratio of period of support to period of non-support follow well the results of other reviewed research. Housden (1964) might lead us to believe that the ratio eventually decreases to a value beneath that of one at very high velocities. If the pattern herein observed holds, this does appear most probably to be the case. Given the velocities herein studied and those which were the concern of Neuman (1967), however, the ratio of period of support to period of non-support approaches one from higher values as the speed of run increases.

Horizontal Distance of Heel to Hip at Contact

The results of the analysis of variance revealed that the variation of the horizontal distance of heel to hip at contact due to the main effects (slope, speed, and individual) and one of the interactions (slope x individual) was highly significant ($p < .01$). Examination of mean differences via the Tukey tests indicated that the three differences between slope group means were highly significant ($p < .01$). The differences between these horizontal distances produced upon all three slopes, therefore, produced on the downhill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between stride rates produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean stride rate produced at 11 feet/second was considerably less than that produced at both 16 feet/second and 21 feet/second, and that the mean stride rate at 16 feet/second was considerably less than that at 21 feet/second.

Depicting the group means for stride rate, Figure 4, page 40, indicates that the group means increased within each of the three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the uphill variable elicited the largest values, the horizontal trials somewhat lesser values, and the downhill condition the lowest values at each of the three speeds.

The results of this investigation, consequently, suggest that the variables of slope, speed, and individual exercised a considerable influence upon stride rate. That is, the stride rate increased as did speed of run, and decreased as the slope became less severe (resistive to movement). Therefore, within the limitations of this study, the results regarding the relationship of speed of run to stride rate follow well the results of all other reviewed research.

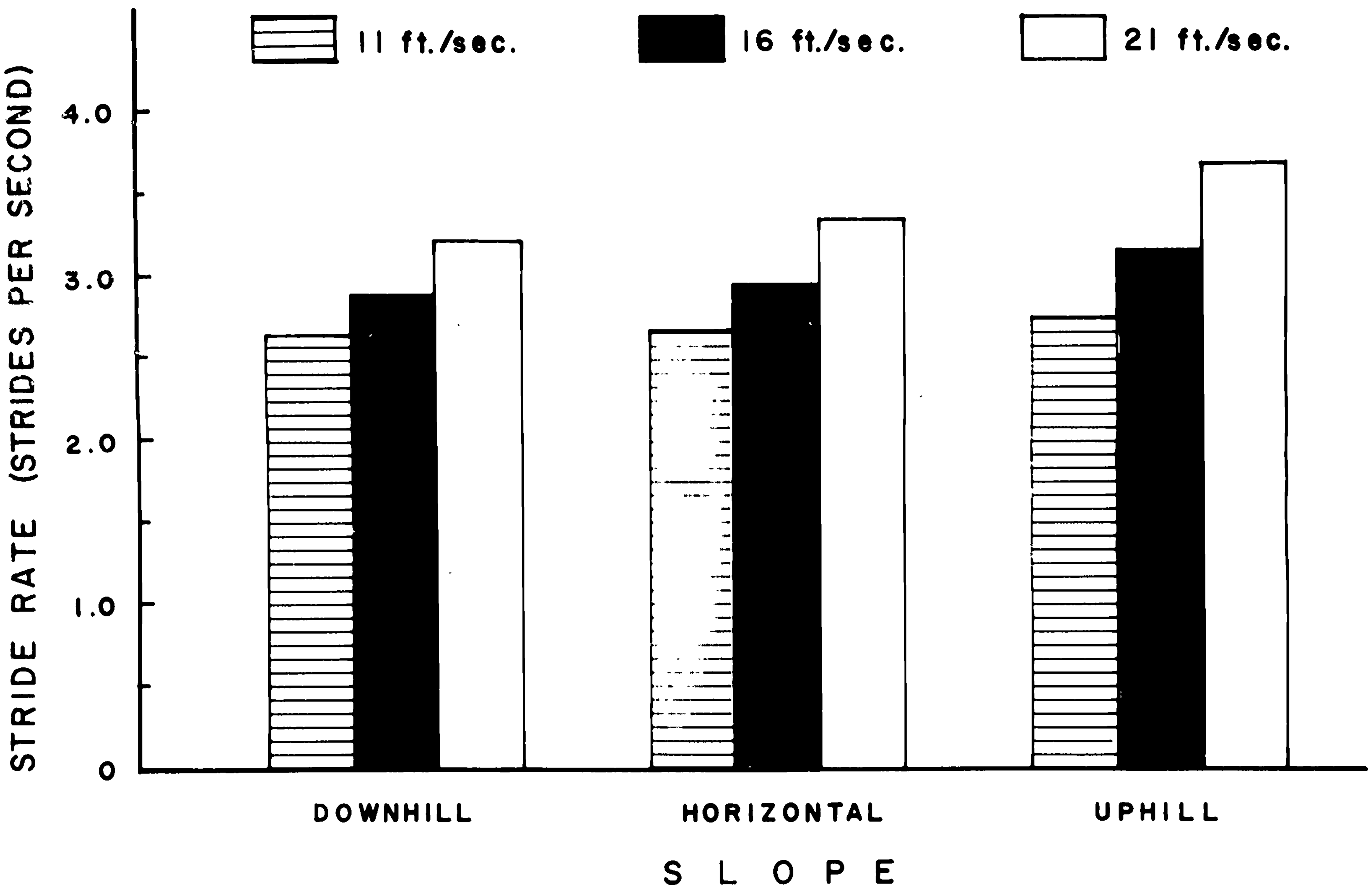

Figure 4. Group means for stride rate within slopes and across speeds. (Performed overground)

Period of Support

The results of the analysis of variance indicated that the variation of the period of support due to the main effects (slope, speed, and individual) and two of the interactions (slope x individual, and speed x individual) was highly significant ($p < .01$).

Further comparison of means via the Tukey tests revealed that two of the three differences between slope group means (horizontal-uphill and uphill-downhill) were highly significant ($p < .01$). The differences between periods of support produced upon these slopes as juxtaposed, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also indicated that the mean period of support while running on a horizontal slope was greater (longer) than that produced on either the uphill or downhill slope, and that exhibited on the downhill slope was greater than that produced on the uphill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between stride rates produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note was that the mean period of support produced at 11 feet/second was greater than that produced at either 16 feet/second or 21 feet/second, and that the mean period of support at 16 feet/second was considerably greater than that at 21 feet/second.

Figure 5, page 43, depicting the group means for the period of support, indicates that the group means decreased within each of the three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the horizontal variable elicited the largest values, the downhill trials somewhat lesser values, and the uphill condition the lowest values at both 11 feet/second and 16 feet/second. At 21 feet/second the downhill variable produced the largest values, the downhill trials somewhat lesser values, and the uphill condition the lowest values.

The results of this investigation, within its conditions and limitations, consequently, suggest that the variables of slope, speed, and individual exercised a considerable influence upon the period of support. That is, the period of support decreased as the speed of run increased; and very generally, it decreased from horizontal, to downhill, to uphill slopes. Therefore, the results of this study regarding the relationship of speed of run to period of support follow well the results of all other reviewed research.

<u>Period of Non-support</u>

The results of the analysis of variance revealed that the variation of the period of non-support due to the main effects (slope, speed, individual) and two of the interactions (slope x speed and slope x individual) was highly significant ($p < .01$). Examination of mean

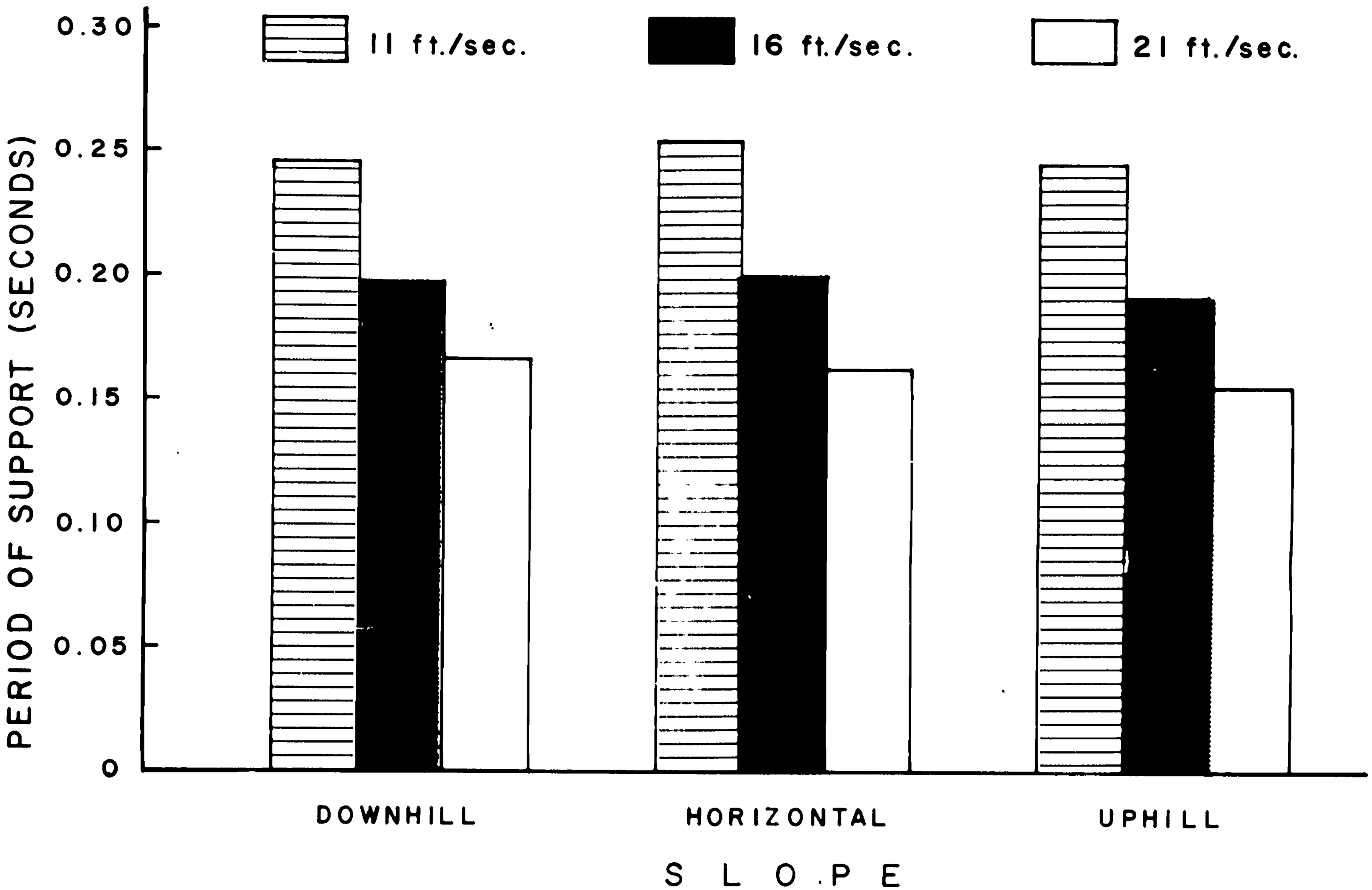

Figure 5. Group means for period of support within slopes and across speeds. (Performed overground)

differences via the Tukey tests indicated that the three differences between slope group means were highly significant ($p < .01$). The differences between periods of non-support produced upon all three slopes, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also revealed that the mean period of non-support while running on a horizontal slope was greater than that produced on the uphill slope, but less than that produced while running on the downhill slope. The mean period of non-support produced on the uphill slope was, therefore, considerably less than that exhibited on the downhill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between periods of non-support produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean period of non-support produced at 11 feet/second was considerably less than that produced at either 16 feet/second or 21 feet/second, and that the mean period of non-support produced at 16 feet/second was considerably greater than that at 21 feet/second.

Figure 6, page 45, depicting the group means for the period of non-support, indicates that the group means increased from 11 feet/second to 16 feet/second, but decreased from 16 feet/second to 21 feet/second within each of

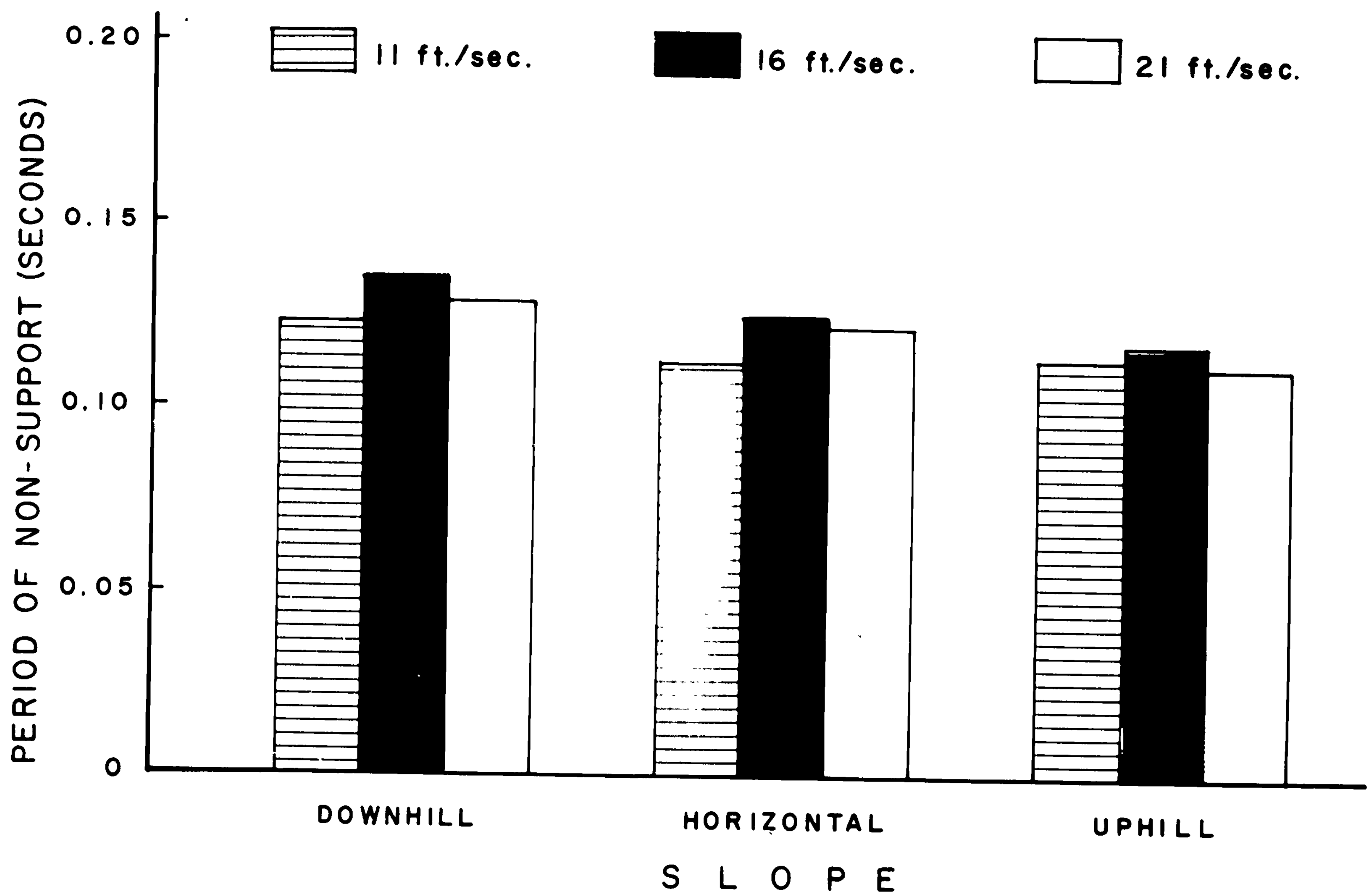

Figure 6. Group means for period of non-support within slopes and across speeds. (Performed overground)

the slopes. The values at 21 feet/second were greater than those at 11 feet/second in horizontal and downhill trials, but less in uphill trials. Across slopes, within speeds, these graphs suggest that the uphill variable elicited the largest values at each of the three speeds. At 11 feet/second the uphill condition produced somewhat lesser values and the horizontal trials the lowest values. At 16 feet/second and 21 feet/second, however, the horizontal condition produced somewhat lesser values and the uphill trials the lowest values.

The results of this investigation, consequently, suggest that the variables of slope, speed, and individual exercised a considerable influence upon the period of non-support. That is, the period of non-support increased as the speed of run increased to a given point only, then commenced to decrease; and very generally it decreased from downhill, to horizontal, to uphill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run and slope to period of non-support support many of the results of the reviewed literature. Without reference to the speed of run, Hopper (1964) and Soule (1966) attested to the absolute desirability of increasing and decreasing the period of non-support, respectively. Neuman (1967) maintained that the period of non-support is positively (directly) affected by alterations in the speed of run. He observed only the first six strides from the blocks, however--a period in which the velocity is not constant. Within the conditions and limitations of this study, the results refute the validity of any statement which fails to refer to the altering character of the relationship in question (speed of run to period of non-support) at divergent speeds of run.

<u>Ratio of Period of Support to Period of Non-support</u>

The results of the analysis of variance indicated that the variation of the ratio of period of support to period of non-support due to the main effects (slope, speed, and individual) and the two-way interactions (slope x speed, slope x individual, speed x individual) was highly significant ($p < .01$). Further comparison of means via the Tukey tests revealed that two of the three differences between slope group means (horizontal-downhill and uphill-downhill) were highly significant ($p < .01$). The differences between the ratio of periods of support to periods of non-support produced upon these slopes as juxtaposed, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also note the mean ratio of period of support to period of non-support while running on a horizontal slope to be less than that produced on the uphill slope, but more than that exhibited while running on the downhill slope. The mean ratio of period of support to period of non-support produced on the uphill slope was, therefore, greater than that produced on the downhill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between ratios of periods of support to periods of non-support produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean ratio of period of support to period of non-support produced at 11 feet/second was considerably greater than that exhibited at either 16 feet/second or 21 feet/second, and that the mean ratio of period of support to period of non-support at 16 feet/second was considerably greater than that at 21 feet/second.

Depicting the group means for the ratio of period of support to period of non-support, Figure 7, page 49, indicates that the group means decreased within each of the three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the horizontal variable elicited the largest values, the uphill trials somewhat lesser values, and the downhill condition the lowest values at 11 feet/second. At 16 feet/second and 21 feet/second the uphill variable produced the largest values, the horizontal trials somewhat lesser values, and the downhill condition the lowest values.

The results of this investigation, consequently, suggest that the variables of slope, speed, and individual

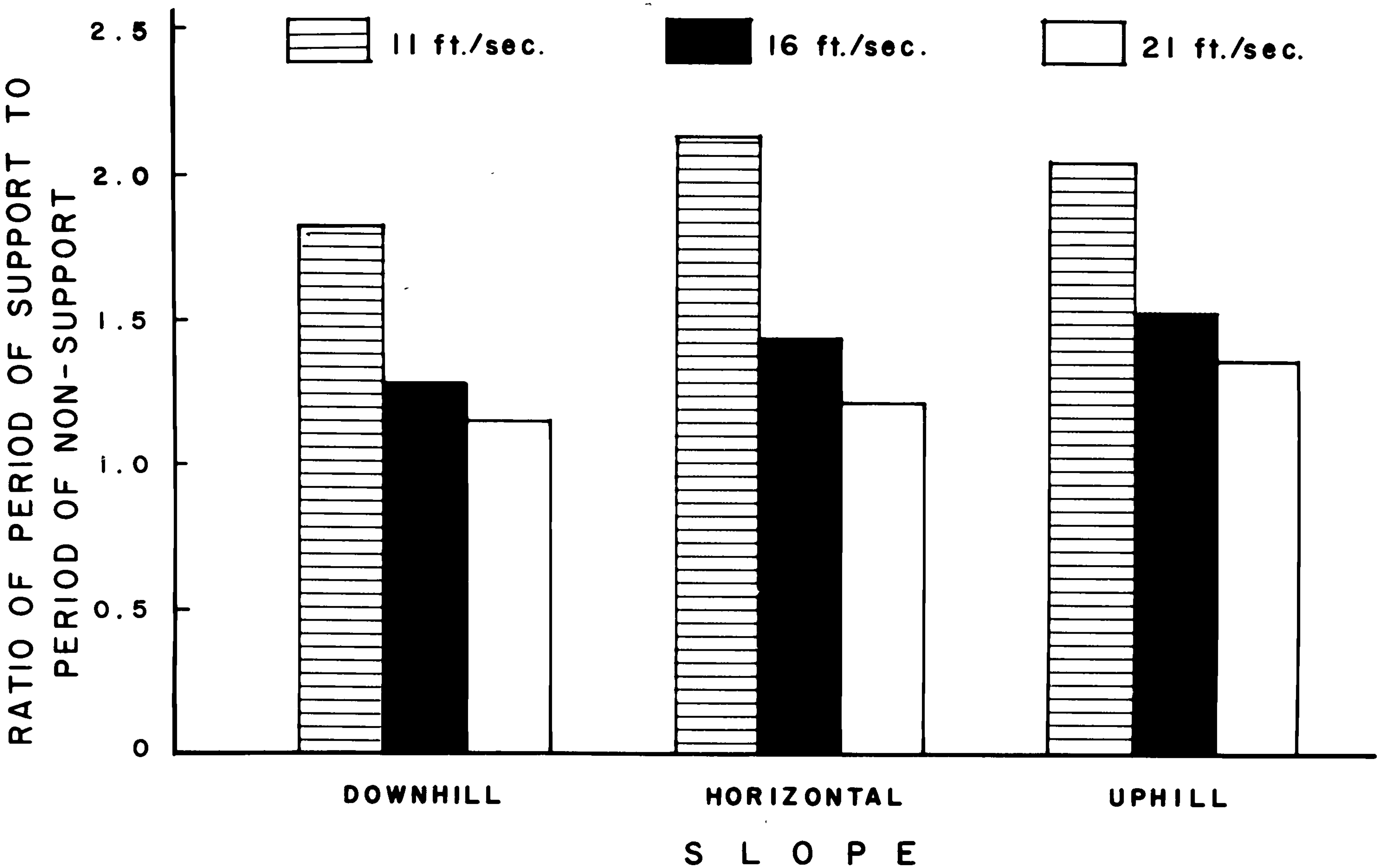

Figure 7. Group means for ratio of period of support to period of non-support within slopes and across speeds. (Performed over-ground)

exercised a considerable influence upon the ratio of period of support to period of non-support. That is, the ratio of period of support to period of non-support decreased as the speed of run increased; and very generally, it decreased from uphill, to horizontal, to downhill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run to the ratio of period of support to period of non-support follow well the results of other reviewed research. Housden (1964) might lead us to believe that the ratio eventually decreases to a value beneath that of one at very high velocities. If the pattern herein observed holds, this does appear most probably to be the case. Given the velocities herein studied and those which were the concern of Neuman (1967), however, the ratio of period of support to period of non-support approaches one from higher values as the speed of run increases.

<u>Horizontal Distance of Heel to Hip at Contact</u>

The results of the analysis of variance revealed that the variation of the horizontal distance of heel to hip at contact due to the main effects (slope, speed, and individual) and one of the interactions (slope x individual) was highly significant ($p < .01$). Examination of mean differences via the Tukey tests indicated that the three differences between slope group means were highly significant ($p < .01$). The differences between these horizontal distances produced upon all three slopes, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also revealed that the mean horizontal distance of heel to hip at contact while running on a horizontal slope was greater than that produced on the uphill slope, but less than that produced while running on the downhill slope. The mean horizontal distance of heel to hip at contact produced on the uphill slope was, therefore, considerably less than that exhibited on the downhill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between these horizontal distances produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean horizontal distance of heel to hip at contact produced at 11 feet/second was considerably less than that produced at either 16 feet/second or 21 feet/second, and that, the mean horizontal distance of heel to hip at contact produced at 16 feet/second was considerably greater than that at 21 feet/second.

Figure 8, page 52, depicting the group means for the horizontal distance of heel to hip at contact, indicates that the group means increased from 11 feet/second to 16 feet/second, but decreased from 16 feet/second to 21 feet/second within the horizontal and uphill slope conditions. They increased as the speed of run increased

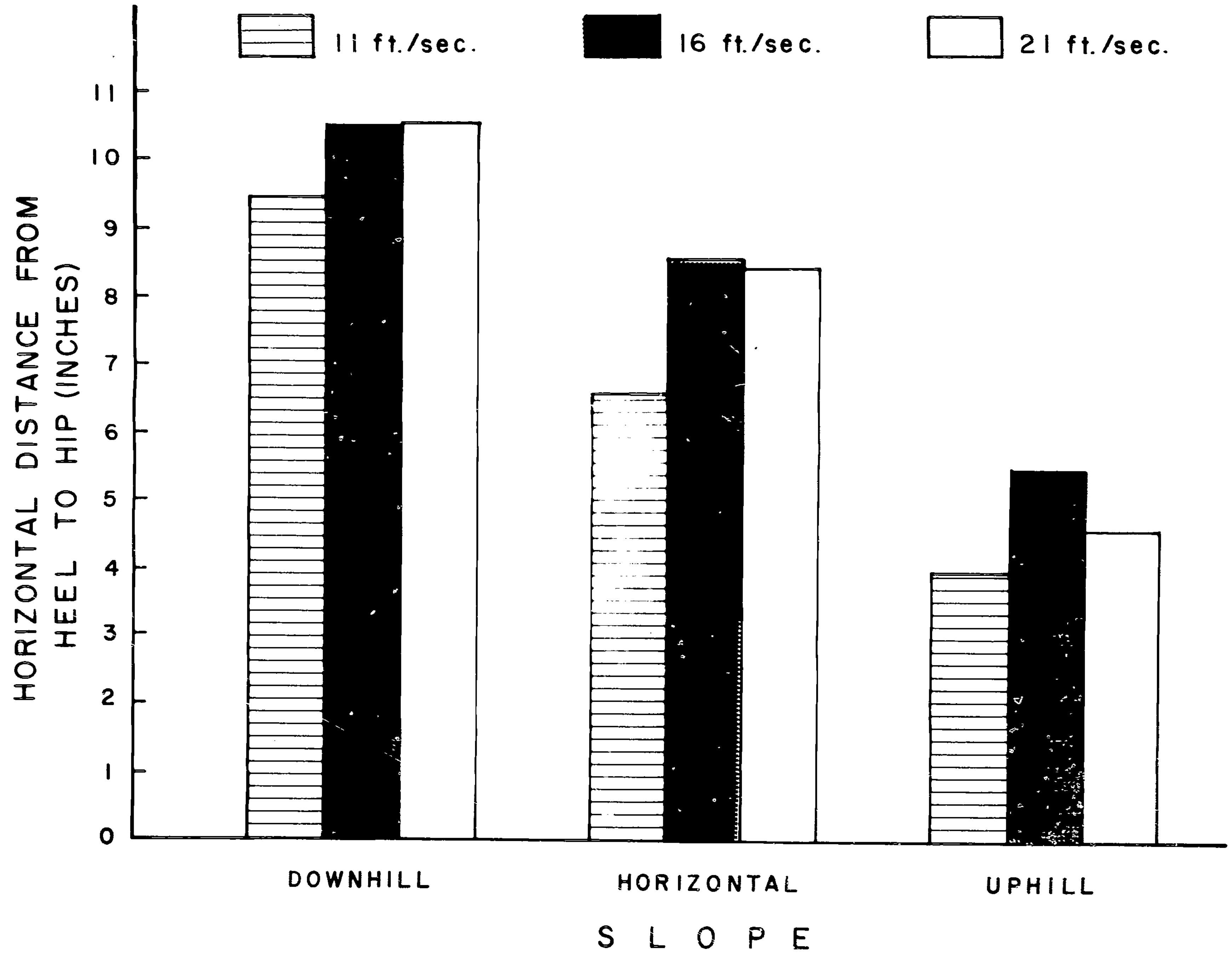

Figure 8. Group means for horizontal distance of heel to hip at contact within slopes and across speeds. (Performed overground)

within the downhill trials, however. Across slopes, within speeds, these graphs suggest that the downhill variable elicited the largest values, the uphill condition somewhat lesser values, and the uphill trials the lowest values at each of the three speeds.

The results of this investigation, consequently, suggest that the horizontal distance of the heel to hip at contact was appreciably altered by the main effects of slope, speed, and individual. That is, this horizontal distance increased to a given point only, then commenced to decrease; and very generally it decreased from downhill, to horizontal, to uphill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run to the horizontal distance of heel to hip at contact follow well those of Fenn (1930), Fenn (1931), and Hopper (1962) in that the heel does inevitably alight to the fore of the hip at contact. Dyson's (1964) statement to the effect that the distance in which the foot lands to the fore of the center of gravity (i.e., hip) decreases as the velocity of run increases, may, however, be supported in part only, as previously observed. The conclusions of Bunn (1955), Housden (1964), Wilt (1964), and Soule (1966) remain entirely unsupported by the results of this study.

Vertical Distance of Height of Body at Contact to Height of Body at Take-off

The results of the analysis of variance indicated that the variation of the vertical distance of height of body at contact to height of body at take-off due to two of the main effects (slope, $p < .01$ and individual, $p < .05$) and one of the interactions (slope x individual, $p < .05$) was significant at the levels noted.

Further comparison of means via the Tukey tests revealed that two of the three differences between slope group means (horizontal-downhill and uphill-downhill) were highly significant ($p < .01$). The differences between these vertical distances produced upon these slopes as juxtaposed, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also indicated that the mean vertical distance of height of body at contact to height of body at take-off while running on a horizontal slope was less than that produced on either the uphill or the downhill slope. While that produced on the downhill slope was greater than that produced on the uphill slope. The Tukey tests also revealed that the three differences between speed group means were non-significant.

Depicting the group means for the vertical distance of height of body at contact to height of body at take-off, Figure 9, page 55, reveals the unpatterned character of movement within slopes. The non-significance of the main

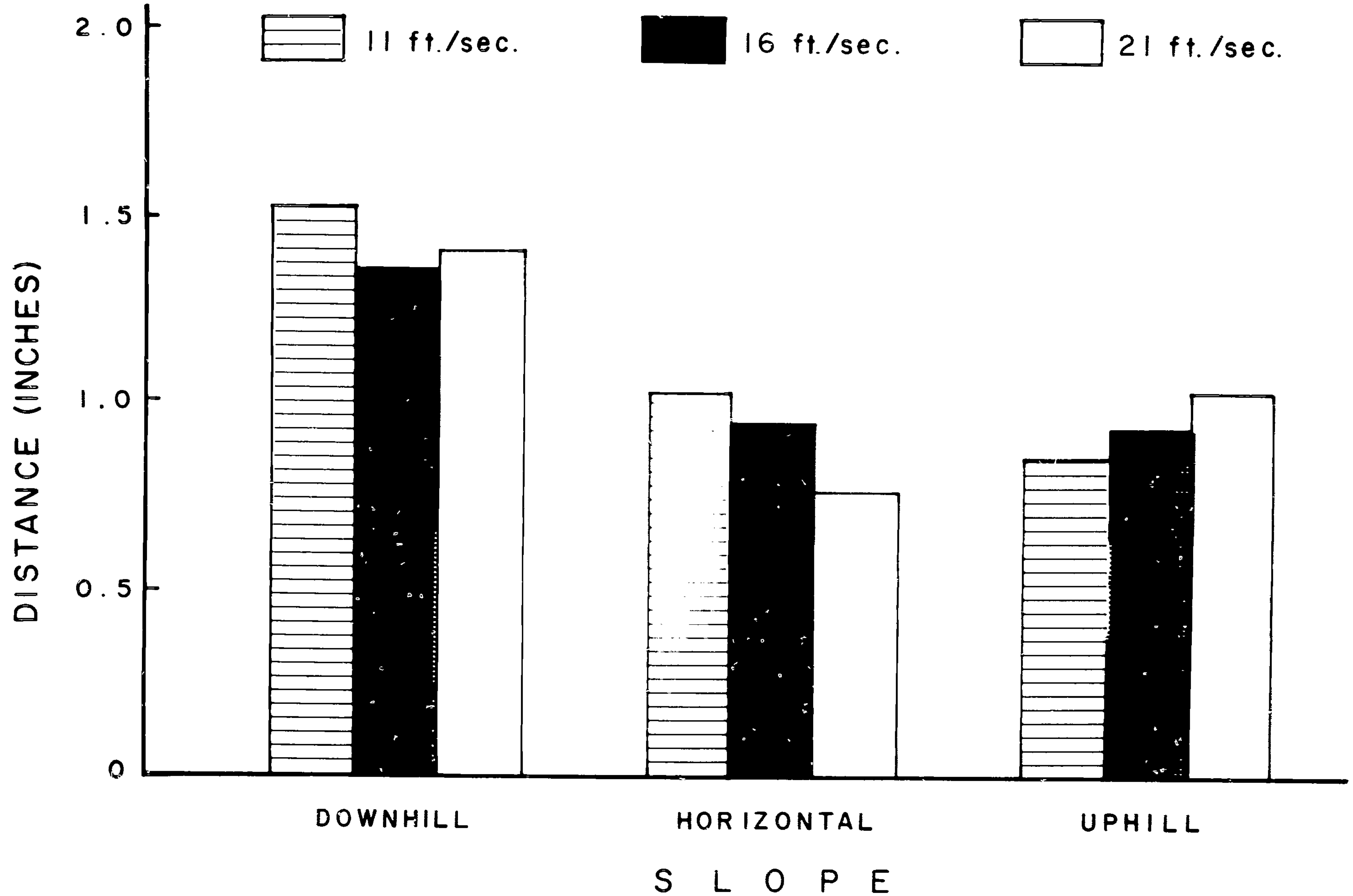

Figure 9. Group means for vertical distance of height of body at contact to height of body at take-off within slopes and across speeds. (Performed overground)

effect of speed rather precludes the value of a within slope analysis. Across slopes, within speeds, however, these graphs suggest that the downhill variable elicited the largest values at all speeds. The uphill condition produced somewhat lesser values and the horizontal trials the lowest values at 11 feet/second and 16 feet/second. While the uphill condition produced somewhat lesser values and the horizontal variable the lowest values at 21 feet/second.

The results of this investigation, consequently, suggest that the variables of slope and individual exercised a considerable influence upon the vertical distance of height of body at contact to height of body at take-off, while that of speed did not. That is, this vertical distance very generally decreased from the downhill, to the uphill, to the horizontal slopes. Variations in the speed of run had little effect upon the vertical distance in question. Therefore, within the limitations of this study, the results regarding the rise of the body during the period of support follow well those of other investigations reviewed.

Vertical Distance of Height of Body at Contact to Height of Body at Temporal Mid-non-support

The results of the analysis of variance revealed that the variation of the vertical distance of height of body at contact to height of body at temporal mid-non-support due to two of the main effects (slope and individual) was highly significant ($p < .01$). The main effect of speed and the three interactions (slope x speed, slope x individual, and speed x individual) produced non-significant results. Examination of mean differences via the Tukey tests indicated that the three differences between slope group means were highly significant ($p < .01$). The differences between these vertical distances produced upon all three slopes, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also revealed that the vertical distances in question while running on a horizontal slope were less than those produced on either the uphill or the downhill slope. While that exhibited on the downhill slope was greater than that produced on the uphill slope. The Tukey tests also indicated that the three differences between speed group means were non-significant.

Figure 10, page 58, depicting the group means for the vertical distance of height of body at contact to height of body at temporal mid-non-support, reveals the unpatterned character of movement within slopes. The non-significance of the main effect of speed rather precludes the value of a within slope analysis. Across slopes, within speeds, however, these graphs suggest that the downhill variable elicited the largest values, the uphill condition somewhat lesser values, and the horizontal trials

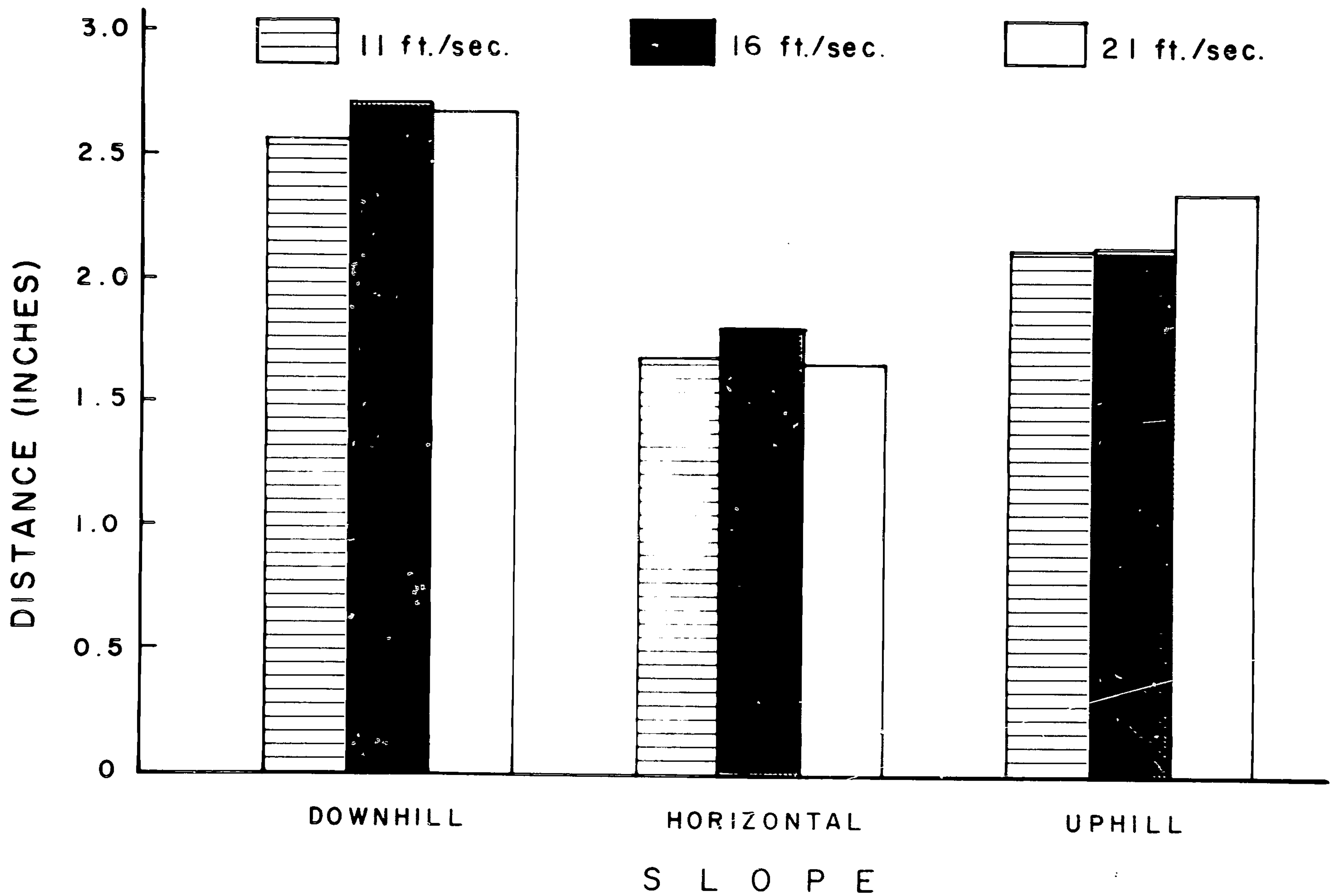

Figure 10. Group means for vertical distance of height of body at contact to height of body at temporal mid-non-support within slopes and across speeds. (Performed overground)

the lowest values at all speeds.

The results of this investigation, consequently, suggest that the variables of slope and individual exercised a considerable influence upon the vertical distance of height of body at contact to height of body at temporal mid-non-support, while that of speed does not. That is, this vertical distance decreases from the downhill, to the uphill, to the horizontal slopes. Variations in the speed of run have little effect upon the vertical distance in question. It must also be observed that all values representing the vertical distance of height of body at contact to height of body at temporal mid-non-support were greater than all corresponding values expressing the vertical distance of height of body at contact to height of body at take-off. The body, therefore, continued to rise beyond take-off. Within the limitations of this study, the results regarding the rise of the body significantly beyond take-off refute those of all other investigations reviewed. Also unsupported is Rapp's (1963) statement suggesting that the speed of run relates inversely to the "body rise."

Body Angle at Contact to Vertical

The results of the analysis of variance indicated that the variation of the body angle at contact to vertical due to the main effects (slope, speed, and individual) and two of the interactions (slope x individual and speed x individual) was highly significant ($p < .01$). Further comparison of means via the Tukey tests revealed that the three differences between slope group means were highly significant ($p < .01$). The differences between these body angles produced upon all three slopes, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also indicated that the mean body angle at contact to vertical while running on a horizontal slope was considerably less than that produced on the uphill slope, but greater than that exhibited while running on the downhill slope. The mean body angle at contact to vertical produced on the uphill slope was, therefore, considerably greater than that produced on the downhill slope. The Tukey tests also revealed that the three differences between speed group means were highly significant ($p < .01$). The differences between these body angles produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean body angle at contact to vertical produced at 11 feet/second was considerably less than that exhibited at 16 feet/second or 21 feet/second, and that the mean body angle at contact to vertical at 16 feet/second was considerably less than that at 21 feet/second.

Depicting the group means for the body angle at contact to vertical, Figure 11, page 61, indicates that the group means increased within each of the three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the uphill variable elicited the

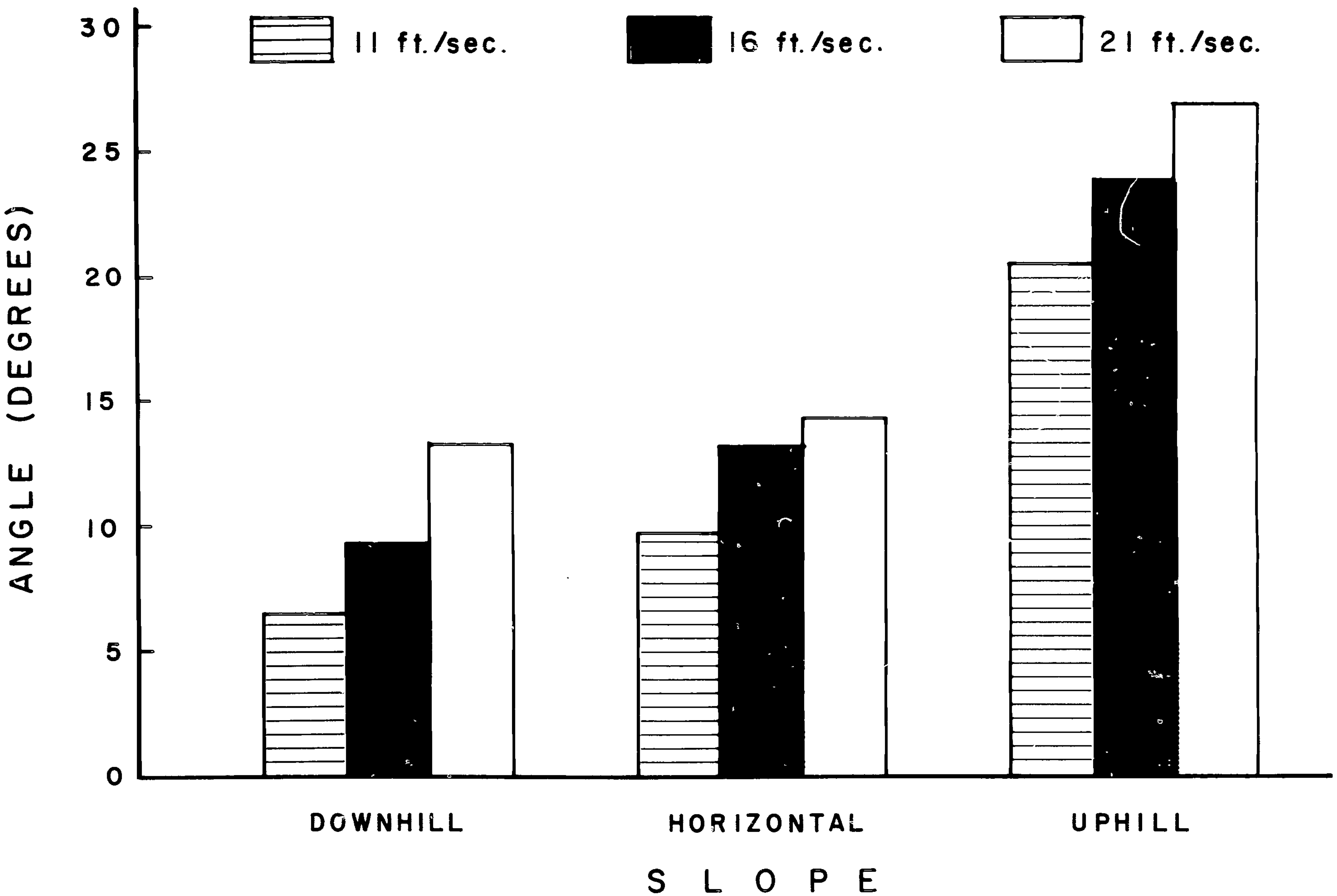

Figure 11. Group means for body angle at contact within slopes and across speeds. (Performed overground)

largest values, the horizontal trials somewhat lesser values, and the downhill condition the lowest values at each of the three speeds.

The results of this investigation, consequently suggest that the body angle at contact to vertical was appreciably altered by the main effects of slope, speed, and individual. That is, the body angle at contact to vertical increased as did the speed of run; and it decreased from the uphill, to the horizontal, to the downhill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run to body angle at contact to vertical follow well the conclusion of Doherty (1963). They do, however, not indicate that the body angle at constant velocities tends to be nearly erect, as have Wilt (1959), Slocum and Bowerman (1963), Wilt (1964), Tricker and Tricker (1967), and Cooper and Glassow (1968). Nor do the results suggest the existence of one body angle for all running speeds, as have Bunn (1955) and Soule (1966).

<u>Angle of the Lower Leg Segment at Contact to Horizontal</u>

The results of the analysis of variance revealed that the variation of the angle of the lower leg segment at contact to horizontal due to the main effects (slope, speed, and individual) and two of the interactions (slope x individual and speed x individual) was highly significant ($p < .01$). Examination of mean differences via the Tukey tests indicated that the three differences between slope group means were highly significant ($p < .01$). The differences between these angles of the lower leg segment produced upon all three slopes, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also indicated that the mean angle of the lower leg segment at contact to horizontal while running on a horizontal slope was considerably less than that produced on the uphill slope, but greater than that exhibited while running on the downhill slope. The mean angle of the lower leg segment at contact to horizontal produced on the uphill slope was, therefore, considerably greater than that produced on the downhill slope. The Tukey tests also revealed that two of the three differences between speed group means (11-21 and 16-21) were highly significant ($p < .01$). The differences between these angles of the lower leg segment produced at these speeds as juxtaposed, therefore, contributed significantly to the variation noted in the main effect of speed. These group means also note that the mean angle of the lower leg segment at contact to horizontal while running at 11 feet/second was less than that produced at either 16 feet/second or 21 feet/second, and that the mean angle of the lower leg segment at contact to horizontal at 16 feet/second was considerably less than that at 21 feet/second.

Figure 12, page 64, depicting the group means for the angle of the lower leg segment at contact to horizontal, indicates that the group means increased as the speed of run increased within the horizontal and uphill slopes, but decreased from 11 feet/second to 16 feet/second but once

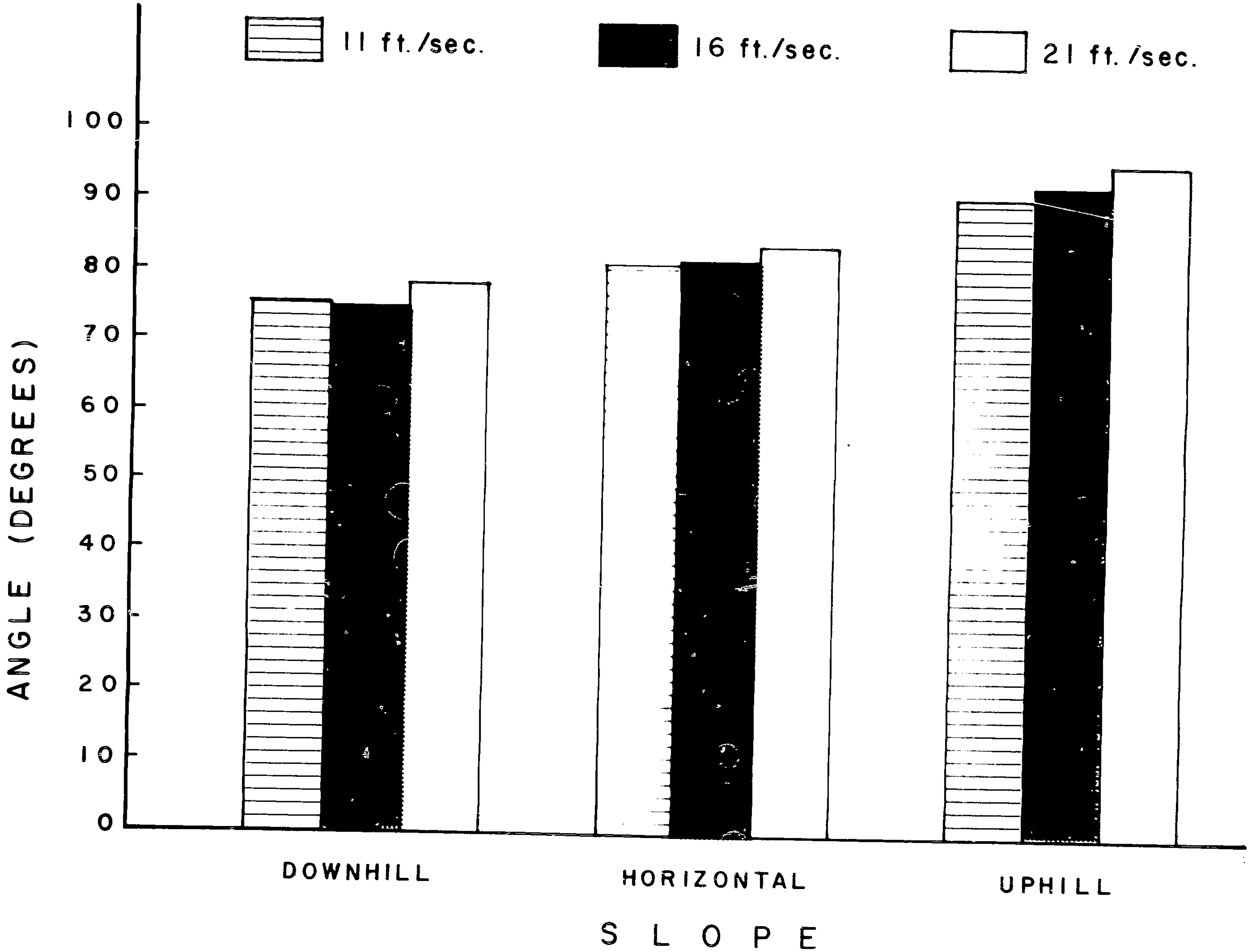

Figure 12. Group means for angle of the leg segment at contact within slopes and across speeds. (Performed overground)

again increased (beyond the 11 feet/second value) at 21 feet/second within the downhill condition. Across slopes, within speeds these graphs suggest that the uphill variable elicited the largest values, the horizontal trials somewhat lesser values, and the downhill condition the lowest values at each of the three speeds.

The results of this investigation, consequently, suggest that the variables of slope, speed, and individual exercised a considerable influence upon the angle of the lower leg segment at contact to horizontal. That is, the angle of the leg segment at contact to horizontal very generally increased as did the speed of run; and it decreased from the uphill, to the horizontal, to the downhill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run to the angle of the lower leg segment at contact to horizontal follow well the results of all other reviewed research.

<u>Angle of the Lower Leg Segment at Take-off to Horizontal</u>

The results of the analysis of variance indicated that the variation of the angle of the lower leg segment at take-off to horizontal due to the main effects (slope, $p < .05$; speed, $p < .01$; and individual, $p < .01$) and one of the interactions (slope x individual, $p < .01$) was statistically significant at the levels noted. Analysis of differences between means for slope and speed via the Tukey tests indicated that only one of the three differences between slope group means (uphill-downhill) was statistically significant ($p < .05$). The differences between these angles of the lower leg segment produced upon these slopes as juxtaposed, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also revealed that the mean angle of the lower leg segment at take-off to horizontal while running on a horizontal slope was greater than that produced on the uphill slope, but less than that exhibited while running on the downhill slope. The mean angle of the lower leg segment at take-off to horizontal produced on the uphill slopes was, therefore, considerably less than that produced on the downhill slope. The Tukey tests also indicated that the three differences between speed group means were highly significant ($p < .01$). The differences between these angles of the lower leg segment produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean angle of the lower leg segment at take-off to horizontal produced at 11 feet/second was considerably greater than that exhibited at either 16 feet/second or 21 feet/second, and that the mean angle of the lower leg segment at take-off to horizontal at 16 feet/second was considerably greater than that at 21 feet/second.

Depicting the group means for the angle of the lower leg segment at contact to horizontal, Figure 13, page 67, indicates that the group means decreased within each of the

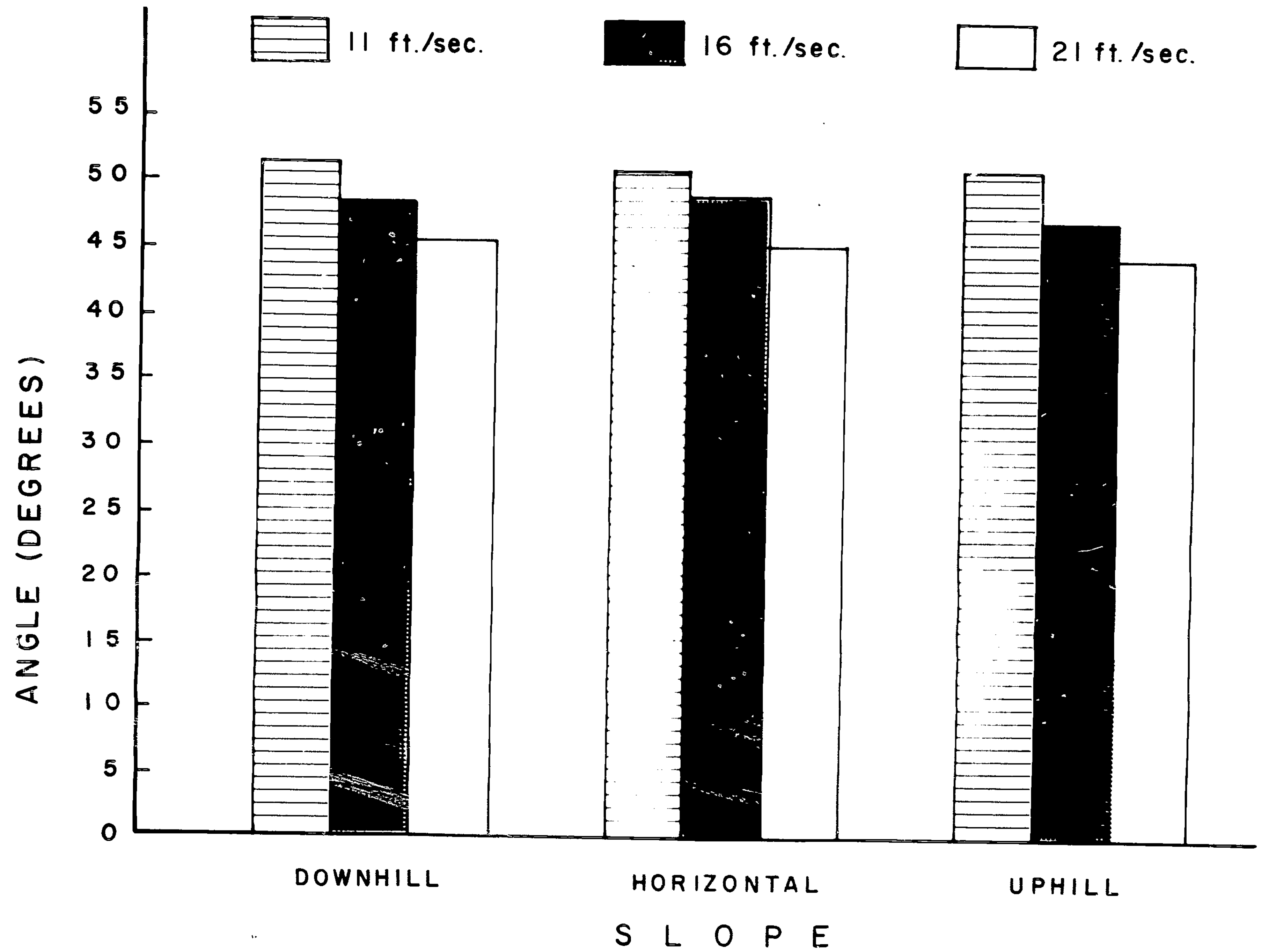

Figure 13. Group means for angle of the leg segment at take-off to horizontal within slopes and across speeds. (Performed overground)

three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the downhill variable elicited the largest values, the horizontal trials somewhat lesser values, and the uphill condition the lowest values at 11 feet/second and 21 feet/second. At 16 feet/second, however, the horizontal trials yielded the largest values, the downhill condition somewhat lesser values, and the uphill variable the lowest values.

The results of this investigation, consequently, suggest that the angle of the lower leg segment at take-off to horizontal was appreciably altered by the main effects of slope, speed and individual. That is, the angle of the lower leg segment at take-off to horizontal decreased as the speed of run increased; and very generally it decreased from the downhill, to the horizontal, to the uphill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run to angle of the lower leg segment at take-off to horizontal follow well the results of other reviewed research. The existence of any one body angle, irrespective of the speed of run, as suggested by Doherty (1963), is refuted, however.

Angle of the Driving Thigh Segment at Take-off to Vertical

The results of the analysis of variance revealed that the variation of the angle of the driving thigh segment at take-off to vertical due to the main effects (slope, speed, and individual) and the interactions (slope x speed, slope x individual, and speed x individual) was highly significant ($p < .01$), but for the speed x individual interaction ($p < .05$). Further comparison of means via the Tukey tests indicated that the three differences between slope group means were statistically significant (horizontal-uphill, $p < .05$); horizontal-downhill, $p < .01$; and uphill-downhill, $p < .01$). The differences between these angles of the driving thigh segment produced upon all three slopes, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also indicated that the mean angle of the driving thigh segment at take-off to vertical while running on a horizontal slope was considerably less than that produced on the uphill slope, but greater than that exhibited while running on the downhill slope. That produced on the uphill slope was, therefore, considerably greater than that produced on the downhill slope. The Tukey tests also revealed that the three differences between speed group means were highly significant ($p < .01$). The differences between these angles of the driving thigh segment produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean angle of the driving thigh segment at take-off to vertical produced at 11 feet/second was considerably less than that exhibited at either 16 feet/second or 21 feet/second, and that the mean angle of the driving thigh segment at take-off to vertical at 16 feet/second was considerably less than that at 21 feet/second.

Figure 14, page 71, depicting the group means for the angle of the driving thigh segment at take-off to vertical, indicates that the group means increased within each of the three slopes as the speed of run increased. Across slopes, within speeds, these graphs suggest that the uphill variable elicited the largest values, the horizontal trials somewhat lesser values, and the downhill condition the lowest values at each of the three speeds.

The results of this investigation, consequently, suggest that the variables of slope, speed, and individual exercised a considerable influence upon the angle of the driving thigh segment at take-off to vertical. That is, the angle of the driving thigh segment at take-off to vertical increased as did the speed of run; and it decreased from the uphill, to the horizontal, to the downhill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run to the angle of the driving thigh segment at take-off to vertical cohere reasonably well with the results of all other reviewed research.

Body Angle at Take-off to Vertical

The results of the analysis of variance indicated that the variation of the body angle at take-off to vertical due to the main effects (slope, speed, and individual) and two of the interactions (slope x individual and speed x individual) was highly significant ($p < .01$). Examination

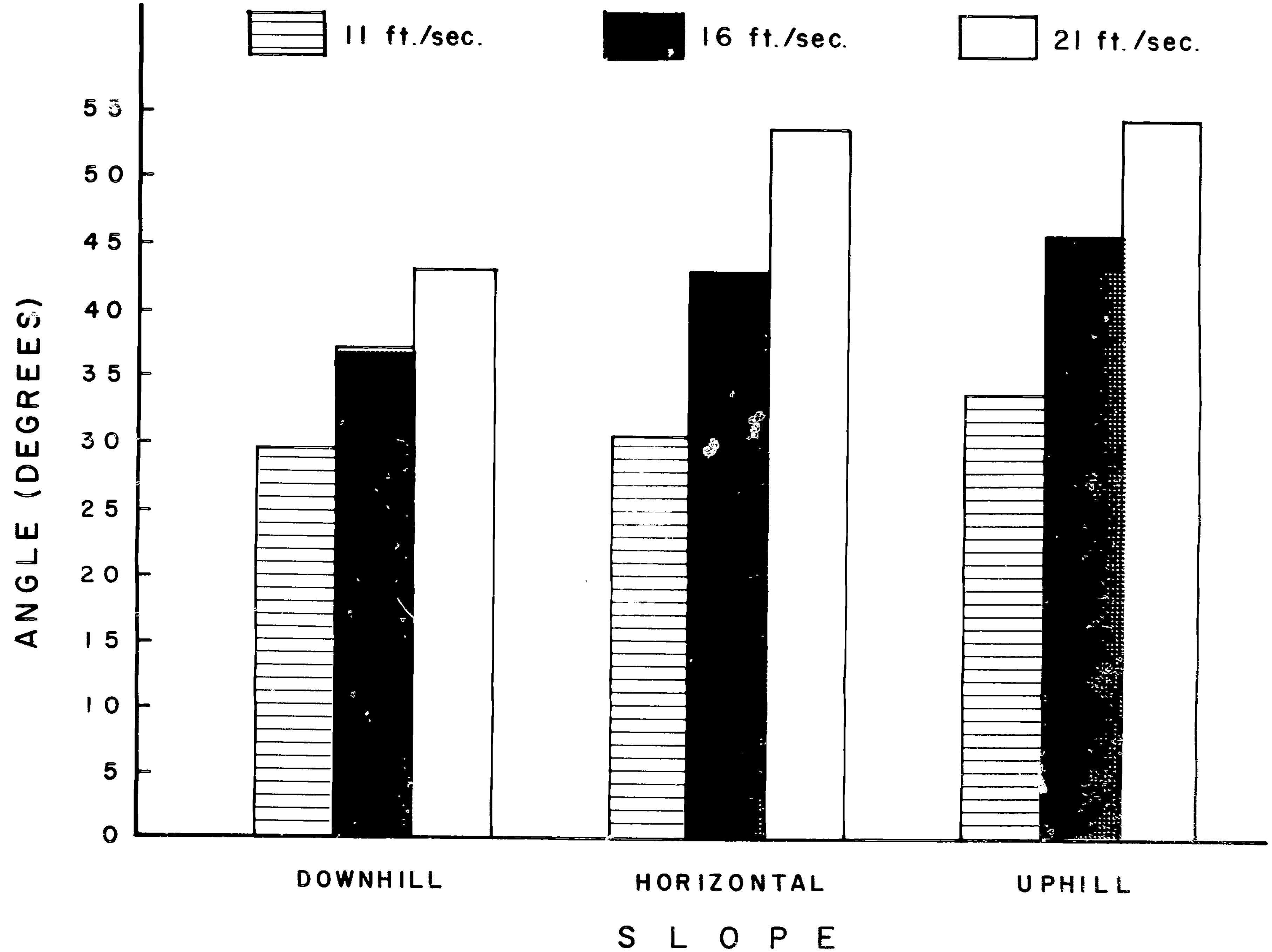

Figure 14. Group means for angle of the driving thigh segment at take-off within slopes and across speeds. (Performed overground)

of mean differences via the Tukey tests revealed that the three differences between slope group means were highly significant ($p < .01$). The differences between these body angles produced upon all three slopes, therefore, contributed significantly to the variation noted in the main effect of slope. These group means also indicated that the mean body angle at take-off to vertical while running on a horizontal slope was less than that produced on the uphill slope, but greater than that exhibited while running on the downhill slope. The mean body angle at take-off to vertical produced on the uphill slope was, therefore, considerably greater than that produced on the downhill slope. The Tukey tests also revealed that the three differences between speed group means were highly significant ($p < .01$). The differences between these body angles produced at all three velocities, therefore, contributed significantly to the variation noted in the main effect of speed. Also of note is that the mean body angle at take-off to vertical produced at 11 feet/second was considerably less than that exhibited at either 16 feet/second or 21 feet/second, and that the mean body angle at take-off to vertical at 16 feet/second was considerably less than that at 21 feet/second.

Depicting the group means for the body angle at take-off to vertical, Figure 15, page 73, indicates that the group means increased as the speed of run increased, but for the 21 feet/second value of the horizontal condition, which decreased to a value beneath that at

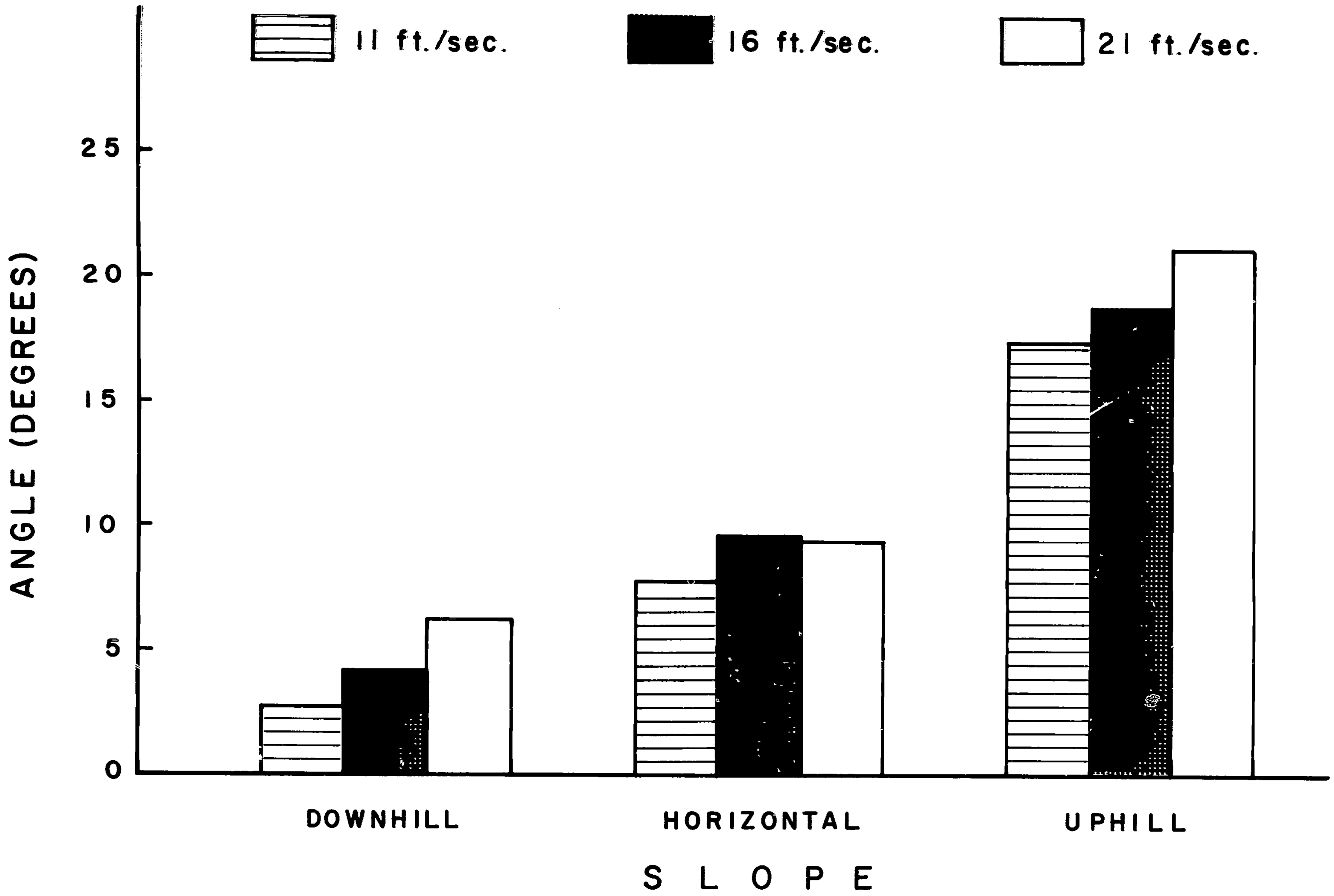

Figure 15. Group means for body angle at take-off to vertical within slopes and across speeds. (Performed overground)

16 feet/second. Across slopes, within speeds, these graphs suggest that the uphill variable elicited the largest values, the horizontal trials somewhat lesser values, and the downhill condition the lowest values at each of the three speeds.

The results of this investigation, consequently, suggest that the body angle at take-off to vertical was appreciably altered by the main effects of slope, speed, and individual. That is, the body angle at take-off to vertical increased as did the speed of run; and it decreased from the uphill, to the horizontal, to the downhill slopes. Therefore, within the limitations of this study, the results regarding the relationship of speed of run to body angle at take-off to vertical follow well the conclusion of Doherty (1963). They do, however, not indicate that the body angle at constant velocities tends to be nearly erect, as have Wilt (1959), Slocum and Bowerman (1963), Wilt (1964), Tricker and Tricker (1967), and Cooper and Glassow (1968). Nor do they suggest the existence of one body angle for all running speeds, as have Bunn (1955) and Soule (1966).

Foot Contact Data

Since the foot contact data were measurable only in terms of nominal scale values, as was previously noted, they were analyzed by merely organizing them and observing the patterns of movement involved as revealed in Table I, page 76. As a result of there being two trials per condition, however, it was on occasion necessary to interpolate between two differing results.

Perhaps the most noticeable feature of the data was the variability of movements betwen subjects (individuals). Also of note was the observation that the area of the plantar surface of the foot to establish initial contact with the supporting surface became more distal (nearer the phalanges) as the speed of run increased over all three slopes. The observations across slopes, within speeds, produced inconclusive results although the downhill condition did appear to produce higher (more distal) results than the horizontal trials, but lower (more proximal) results than the uphill condition. Regardless of the speed of the run or the slope upon w-ich the running movement occurred, however, the heel inevitably contacted the track at some point during the period of support. And the initial contact always occurred on the lateral border of the foot.

The results of this investigation, consequently, suggest that speed and individual exercised a considerable influence upon foot contact. That is, the foot contact became progressively higher (more distal) as the speed of run increased. Variations in the slope had little detectable effect upon foot contact. Therefore, within the limitations of this study, the results regarding the relationship of speed of run to foot contact follow well the results of all other research, but Fenn (1930) and Cooper and Glassow (1963). The results of this investigation do not report, then, the prevalence or desirability of any one mode of foot contact, nor do they indicate a "full foot contact" to occur under any condition.

TABLE I

FOOT CONTACT DATA BY SLOPE AND SPEED
(N = 16)

Point of Foot Contact	Horizontal Feet/Second			Uphill Feet/Second			Downhill Feet/Second		
	11	16	21	11	16	21	11	16	21
HEEL									
Lateral High-Heel	6[a]	2	2	1	0	0	4	2	1
Lateral Heel	3	1	0	1	0	0	1	1	2
Lateral Low-Heel	1	4	3	2	2	0	1	2	3
Lateral Heel-Ball	1	1	2	6	4	4	2	2	0
Lateral Low-Ball	2	2	0	0	1	1	1	0	0
Lateral Ball	3	4	4	5	5	1	3	4	3
Lateral High-Ball	0	2	4	1	3	5	4	5	6
Lateral Ball-Toe	0	0	1	0	1	5	0	0	1
TOE									

[a]Refers to the number of subjects producing this result.

CHAPTER V

ANALYSIS AND INTERPRETATION OF THE RESULTS

Since so many (fourteen) elements of the running stride have been considered for study, discussion of each of the fourteen has been included in Chapter IV. The comparison of the results of this study to those of others has also been included in Chapter IV. This analysis and interpretation of the results is, therefore, an attempt to explicate the terms in which one element accompanies (not causes) another, and the manner in which any given element is affected by variations in slope and/or speed.

Within the limitations of this study, it is apparent that the variation in the elements of the running stride under scrutiny due to the main effects of slope, speed, and individual is statistically significant for all elements, except those two involving vertical displacement and that of foot contact. Only slope and individual are significant in the case of the former, and speed and individual in the case of the latter. It is also apparent that the effects of slope and speed do not exercise a uniform influence upon individuals, as the slope x individual and speed x individual interactions indicate.

More specifically, as the speed of run increases the stride length, stride rate, period of non-support, body angle at contact to vertical, angle of the lower leg segment at contact to horizontal, angle of the driving thigh segment at take-off to vertical, and the body angle at take-off to vertical likewise increase. Conversely, the period of support, the ratio of period of support to period of non-support, and the angle of the lower leg segment at take-off to horizontal decrease. The point of foot contact becomes higher (more distal), and the vertical distance of height of body at contact to height of body at take-off and the vertical distance of height of body at contact to height of body at temporal mid-non-support exhibit a non-significant effect to alterations in the speed of run. The horizontal distance of the heel to hip at contact initially increases then commences to decrease.

An increase in the speed of run is, therefore, accompanied by an increase in both stride length and stride rate. The downhill slope, however, has the greatest, and the uphill slope the least, effect upon stride length, while the inverse is true of stride rate. Within given speeds, consequently, the most severe slopes (resistive to movement) elicited higher stride rates and shorter stride lengths than did others.

Since the period of support decreases and the period of non-support increases as the speed of run increases, the ratio of period of support to period of non-support necessarily decreases--approaches unity--as increments in the speed of run occur. The runner, therefore, becomes more responsive to the running surface (applies greater forces more rapidly) as the speed of run increases. As such, increasingly greater periods of time are spent in non-support as the stride length increases.

The horizontal slope has the greatest, and the uphill slope the least effect upon the period of support. The downhill slope has the greatest, and the uphill slope the least, effect upon the period of non-support. While the uphill slope has the greatest, and the downhill slope the least, effect upon the ratio of period of support to period of non-support. This tends to indicate that the effects of slope upon these periods are difficult to generalize, although the ratio is most influenced by the most severe slopes (resistive to movement).

A decrease in the horizontal distance of the heel to hip at contact is accompanied by an increase in the angle of the lower leg segment at contact to horizontal as the speed of run increases. The heel, landing nearer the hip, virtually permits the lower leg segment to describe a larger angle to horizontal, and the foot to alight somewhat more distally on its plantar surface. As a result, the retarding effect upon the speed of run generally considered to accompany the existence of this horizontal distance in front of the hip is reduced as the speed of run increases. The least severe slopes (resistive to movement) have the greatest effect upon the horizontal distance of the heel to hip at contact, while the most severe slopes (resistive to movement) most effect the angle of the lower leg segment at contact to horizontal. Inevitably, however, the foot does indeed alight in front of the hip.

Although the vertical distance of height of body at contact to height of body at take-off and the vertical distance of height of body at contact to height of body at temporal mid-non-support are not appreciably effected by variations in speed, they are significantly effected by hill, as opposed to horizontal, conditions (downhill and uphill). Because the magnitude of the values associated with the vertical distance of height of body at contact to height of body at temporal mid-non-support is greater than those associated with the vertical distance of the height of body at contact to height of body at take-off the body continues to rise beyond the moment of take-off.

The body angle at contact to vertical and the body angle at take-off to vertical both increase with an increment in speed, and are both significantly effected by the most severe slopes (resistive to movement). Because the magnitude of the values associated with the body angle at contact to vertical is greater than those associated with the body angle at take-off to vertical, there does appear to be a vacillating movement of the trunk segment involved. This phenomenon may perhaps be attributed to the "hinged moment" of the alighting foot-leg-thigh complex, as it conserves angular momentum of the landing lower appendage by transferring it to the trunk segment. As this occurs a rotation of the trunk counters that of the appendage in question and the body angle thereby increases. At take-off the supporting foot moves to the rear of the trunk segment eliciting a counter rotation which decreases the body angle.

The angle of the lower leg segment at take-off to horizontal decreases as the speed of run increases; thus, greater horizontal vector components are contributed to the movement than at somewhat lower velocities. This angle is most effected by the least severe slopes (resistive to movement), as most probably the freedom to use a larger range of movement is greater, and the effect of gravity less impinging. Since the angle of the driving thigh segment at take-off to vertical, conversely, increases as does the speed of run, the most beneficial angle of take-off and application of force is achieved. This increasing force may in part explain the increment in the duration of the period of non-support as the speed of run increases, despite the accompanying decrement in the angle of the lower leg segment at take-off to horizontal. The angle of the driving thigh segment at take-off to vertical is most effected by the most demanding (severe) slopes.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The summary of this investigation is presented in terms of the origin and significance of the study, the statement of the problem, the experimental procedures, and the results. Conclusions are presented with suggestions for further research.

Origin and Significance of the Study

Of the research which has been accomplished with regard to the mechanics of running, none has been concerned with the manner in which the mechanical components of the running stride are altered while running up and/or down slopes, and few have studied the alteration of stride mechanics which accompany variations in running tempos. Of those which have treated these problems very few indeed have been concerned with the collection, organization, analysis, and interpretation of empirical data. In the mid-twentieth century when the philosophical; and biological, physical, and social scientific implications of athletics are so great, an improved understanding of, and consensus concerning, its nature appears desirable.

Statement of the Problem

The purpose of this study has been to investigate the manner in which selected mechanical elements of the running stride are altered with accompanying variations in the speed of run and the slope upon which the running occurs. The mechanical aspects of the running stride chosen for study are: stride length, stride rate, period of support, period of non-support, ratio of period of support to period of non-support, horizontal distance of heel to hip at contact, vertical distance of height of body at contact to height of body at take-off, vertical distance of height of body at contact to height of body at temporal mid-non-support, body angle at contact to vertical, angle of the lower leg segment at contact to horizontal, angle of the lower leg segment at take-off to horizontal, angle of the driving thigh segment at take-off to vertical, body angle at take-off to vertical, and foot contact data.

<u>Experimental Procedures</u>

Sixteen intercollegiate runners were marked at reference points of the body pertinent to this study and filmed while twice running: 1) on a flat (horizontal) surface, 2) uphill on a 10 per cent slope, and 3) downhill on a 10 per cent slope at the constant velocities of 11, 16, and 21 feet/second. With the use of cinematographic techniques appropriate data were extracted from the film; so that, either they or their modifications yielded the 14 mechanical elements of the running stride under scrutiny. All measurements were extracted with reference to the running surface, as opposed to the horizontal

The collected data were then organized and presented to FORTRAN IV ANOVR, a general purpose analysis of variance routine. Tukey tests were subsequently performed in an attempt to determine which differences between groups had contributed to a significant F-ratio, and in which direction the variation had occurred.

Results

The results of the analyses of variance indicate significant F-ratios for the main effects (slope, speed, and individual) of all mechanical elements of the running stride in question, except those two involving vertical displacement in which only slope and individual were significant. Foot contact appeared to be influenced by speed and individual only.

More specifically, as the speed of run increases the stride length, stride rate, period of non-support, body angle at contact to vertical, angle of the lower leg segment at contact to horizontal, angle of the driving thigh segment at take-off to vertical, and the body angle at take-off to vertical likewise increase. Conversely, the ratio of period of support, period of support to period of non-support, and the angle of the lower leg segment at take-off to horizontal decrease. The point of foot contact becomes progressively higher (more distal). The horizontal distance of the heel to hip at contact initially increases then commences to decrease. The effect of the three slopes upon running mechanics varied more widely than that of speed, and is, therefore, difficult to categorize.

Conclusions

Within the limitations of this study, it is concluded that the biomechanics of the running stride are significantly altered by changes in speed, and the slope of the running surface. It is also apparent that the effects of slope and speed do not exercise a uniform influence upon individuals. And that the slopes and velocities chosen as experimental conditions are sufficiently dissimilar to effect detectable variations in stride mechanics.

Suggestions for Further Research

Statements of recommendation for further research are normally couched in terms of removing or reducing the limitations of the study. Those limitations most easily eliminated include: the unsatisfactory control of the point at which the foot alights (treating the running surface as a long jump runway with the take-off board in the most desirable area might prove helpful); the inadequate marking of the plane of the running surface; and the unsatisfactory system of tape marking pertinent reference points on the athletes' bodies, which included marking the athletes' clothing.

Of further significance, of course, would be a segmental analysis of the center of gravity of the body designed to answer questions, similar in some respects, to those of this investigation. And a study involving more divergent slopes and speeds might prove to be of interest.

The impact of investigations such as this awaits the application of scientific research to sport skills. Such research must be utilized to better explain and improve performance.

BIBLIOGRAPHY

BIBLIOGRAPHY

A. BOOKS

Alder, Henry L. and Edward B. Roessler. Introduction to Probability and Statistics. Third edition. San Francisco: W. H. Freeman and Company, 1964.

Bunn, John W. Scientific Principles of Coaching. Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1955.

Cooper, John M. and Ruth B. Glassow. Kinesiology. First edition. St. Louis: The C. V. Mosby Co., 1963.

Cooper, John M. and Ruth B. Glassow. Kinesiology. Second edition. St. Louis: The C. V. Mosby Co., 1968.

Demeny, George. Mechanisme et Education des Mouvements. Paris: F. Alcan, 1924. Cited by Scott, Gladys (ed.). Research Methods in Health, Physical Education, Recreation. Second edition. Washington: American Association for Health, Physical Education, and Recreation, 1959.

Doherty, J. Kenneth. Modern Track and Field. Second edition. Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1963.

Dyson, Geoffrey H. G. The Mechanics of Athletics. Third edition. London: University of London Press, 1964.

Marey, E. J. Animal Mechanism. New York: D. Appleton-Century Co., 1887. Cited by Scott, Gladys (ed.). Research Methods in Health, Physical Education, Recreation. Second edition. Washington: American Association for Health, Physical Education, and Recreation, 1959.

Rasch, Philip J. and Roger K. Burke. Kinesiology and Applied Anatomy. Second edition. Philadelphia: Lea and Febiger, 1963.

Scott, Gladys (ed.). Research Methods in Health, Physical Education, Recreation. Second edition. Washington: American Association for Health, Physical Education, and Recreation, 1959.

Snedecor, George W. Statistical Methods. Fifth edition. Ames, Iowa: The Iowa State University Press, 1956.

Tricker, R. A. R. and B. J. K. Tricker. The Science of Movement. New York: The American Elsevier Publishing Company, 1967.

Weber, E. and W. Weber. Mechanik der Menschlichen, Geswerkzeuge: Gotingen, 1836. Cited by Scott, Gladys (ed.). Research Methods in Health, Physical Education, Recreation. Second edition. Washington: American Association for Health, Physical Education, and Recreation, 1959.

Williams, Marian and Herbert Lissner. Biomechanics of Human Motion. Philadelphia: W. B. Saunders Company, 1962.

Winer, B. J. Statistical Principles in Experimental Design. New York: McGraw-Hill Book Company, 1962.

B. PERIODICALS

Cavagna, G. A., R. Margaria, and E. Arcelli. "A High-Speed Motion Picture Analysis of the Work Performed in Sprint Running," Encyclopedia Cinematographica, V (December, 1965), 309-319.

Cavagna, G. A., F. P. Sailiene, and R. Margaria. "Mechanical Work in Running," Journal of Applied Physiology, XIX (March, 1964), 249-256.

Chapman, H. A. L. "Forward Lean in Sprinting," Track Technique, September, 1961, 133.

Cureton, Thomas K. "Mechanics of Track Running," Scholastic Coach, IV (1935), 7-10.

Deshon, Deane E. and Richard C. Nelson. "A Cinematographical Analysis of Sprint Running," The Research Quarterly, XXXV (December, 1964), 451-455.

Fenn, Wallace O. "A Cinematographic Study of Sprinters," The Scientific Monthly, XXXII (1931), 346-354.

Fenn, Wallace O. "Frictional and Kinetic Factors in Work of Sprint Running," American Journal of Physiology, XCII (1929), 583-611.

Fenn, Wallace O. "Work Against Gravity and Work Due to Velocity Changes in Running," American Journal of Physiology, XCIII (1930), 433-462.

Gibson, John A. "Middle Distance Training and Form," Scholastic Coach, XXII (April, 1953), 16.

Gollnick, Philip D. and Peter V. Karpovich. "Electrogoniometric Study of Locomotion and Some Athletic Movements," Research Quarterly, XXXV (October, 1964), 357-369.

Hopper, Bernard J. "The Mechanics of Arm Action in Running," Track Technique, September, 1964, 520-522.

Hopper, Bernard J. "Rotation--A Vital Factor in Athletic Technique," Track Technique, December, 1962, 306-310.

Kroll, W. and W. Morenz. "The Athletic Run as Quadruped Motion," Arbeitphysiologie, 1931, 228-237.

Nelson, Richard C. and Chauncey A. Morehouse. "Statistical Procedures Used in Multiple-group Experiments," Research Quarterly, XXXVII (October, 1966), 441-445.

Nett, Toni. "Foot Plant in Running," Track Technique, March, 1964, 462-463.

Neuman, Jan. "Studium Struktury Pohybove Cinnosti Pri Startovnim Roybehu (Study of Motion Structure During Start Period)," Teor. Praxe tel. Vych., XIV (1966), 85-90.

Neuman, Jan. "Casova Charakteristika Sprinterskeho Behu 12-13 Letych Chlapcu (Chronometrical Characteristics of the Sprint of 12-13 Year Old Boys)," Teor. Praxe tel. Vych., XV (1967,a), 292-297.

Neuman, Jan. "Rychlost Behu V Prvnich Metrech Sprinterske Trate (The Speed in Running the First Meters of Track Sprinting)," Teor. Praxe tel. Vych., XV (1967,b), 464-471.

Powell, John T. "Basic Mechanical Principles of Running," Track Technique, September, 1960, 9-11.

Soule, R. G. "Mechanics of the Distance Stride," Scholastic Coach, XXXV (February, 1966), 44-46.

Sylvia, A. J. "Body Mechanics of Sprinting," Athletic Journal, XLVI (March, 1966), 14-15.

Wilt, Fred. "Running Form," Scholastic Coach, XXVIII (March, 1959), 10-11.

C. ARTICLES IN COLLECTIONS

Housden, Fred. "Mechanical Analysis of the Running Movement," Run, Run, Run, Fred Wilt, editor. Los Altos, Calif.: Track and Field News, Inc., 1964, 240-242.

Rompotti, Kalevi. "A Study of Stride Length in Running," International Track and Field Digest, Don Canham and Phil Diamond, editors. National Collegiate Track and Field Coaches Association Clinic Notes of the First International Track and Field Coaches Clinic. Ann Arbor, Michigan: Champions on Film, 1956, 249-256.

Slocum, Donald B. and Bill Bowerman. "The Biomechanics of Running," Track in Theory and Technique, Thomas P. Rosandich, editor. Richmond, Calif.: Worldwide Publishing Company, 1963, 67-73.

Wilt, Fred. "Fundamental Movements in Running," Run, Run, Run, Fred Wilt, editor. Los Altos, Calif.: Track and Field News, Inc., 1964, 235-239.

D. UNPUBLISHED MATERIALS

Beck, Marjory C. "The Path of the Center of Gravity During Running in Boys, Grades One to Six." Unpublished Doctoral thesis, The University of Wisconsin, Madison, 1965.

Dittmer, Joann. "A Kinematic Analysis of the Development of the Running Pattern of Grade School Girls and Certain Factors Which Distinguish Good from Poor Performance at the Observed Ages." Unpublished Master's thesis, The University of Wisconsin, Madison, 1962.

Fortney, Virginia L. "The Swinging Limb in Running of Boys Ages Seven Through Eleven." Unpublished Master's thesis, The University of Wisconsin, Madison, 1963.

Rapp, Kenneth E. "Running Velocity: Body-Rise and Stride-Length." Unpublished Master's thesis, The State University of Iowa, Cedar Falls, 1963.

Slater-Hammel, Arthur. "Leg Rate and Length of Stride in Sprinting: An Experimental Study of the Relation Between Rate of Stride and Length of Stride and the Relative Importance of these Factors in Sprinting." Unpublished Master's thesis, Oberline College, Oberlin, 1939.

Southern Illinois University. "FORTRAN IV ANOVR: Analysis of Variance with Repeated Measures." University Park, Pennsylvania: The Pennsylvania State University, 1968. (Mimeographed.)

White, Raymond V. "A Cinematographical Study of Certain Body Mechanics in Running of Two Highly-skilled Runners." University Park, Pennsylvania: The Pennsylvania State University, 1966. (Typewritten.)

APPENDIX A

ANALYSIS OF VARIANCE TABLES

TABLE II

SUMMARY OF ANALYSIS OF VARIANCE
FOR STRIDE LENGTH

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	32311.20	287			
Slope	3109.26	2	1554.63	178.405	.01
Speed	23459.70	2	11729.90	1346.085	.01
Slope x speed	506.06	4	126.52	14.518	.01
Individual	2118.96	15	141.26	16.211	.01
Slope x individual	761.64	30	25.39	2.913	.01
Speed x individual	619.08	30	20.64	2.368	.01
Slope x speed x individual	481.68	60	8.03	0.921	
Error	1254.82	144	8.71		

TABLE III

SUMMARY OF ANALYSIS OF VARIANCE
FOR STRIDE RATE

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	45.50	287			
Slope	4.29	2	2.14	93.109	.01
Speed	26.31	2	13.16	571.232	.01
Slope x speed	1.25	4	0.31	13.573	.01
Individual	6.53	15	0.44	18.897	.01
Slope x individual	1.56	30	0.05	2.262	.01
Speed x individual	1.18	30	0.04	1.703	.01
Slope x speed x individual	1.07	60	0.02	0.775	
Error	3.32	144	0.02		

TABLE IV

SUMMARY OF ANALYSIS OF VARIANCE
FOR PERIOD OF SUPPORT

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	0.470	287			
Slope	0.004	2	0.00200	15.448	.01
Speed	0.372	2	0.18611	1435.475	.01
Slope x speed	0.001	4	0.00026	2.035	
Individual	0.050	15	0.00335	25.806	.01
Slope x individual	0.008	30	0.00026	2.025	.01
Speed x individual	0.007	30	0.00023	1.755	.01
Slope x speed x individual	0.005	60	0.00008	0.595	
Error	0.019	144	0.00013		

TABLE V

SUMMARY OF ANALYSIS OF VARIANCE
FOR PERIOD OF NON-SUPPORT

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	0.130	287			
Slope	0.030	2	0.0152	86.995	.01
Speed	0.011	2	0.0053	30.136	.01
Slope x speed	0.004	4	0.0010	5.574	.01
Individual	0.025	15	0.0017	9.512	.01
Slope x individual	0.015	30	0.0005	2.962	.01
Speed x individual	0.007	30	0.0002	1.352	
Slope x speed x individual	0.010	60	0.0002	0.921	
Error	0.026	144	0.0002		

TABLE VI

SUMMARY OF ANALYSIS OF VARIANCE FOR RATIO OF PERIOD OF SUPPORT TO PERIOD OF NON-SUPPORT

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	55.47	287			
Slope	2.46	2	1.232	28.627	.01
Speed	31.36	2	15.678	364.317	.01
Slope x speed	0.71	4	0.177	4.120	.01
Individual	7.60	15	0.507	11.776	.01
Slope x individual	2.77	30	0.092	2.149	.01
Speed x individual	2.35	30	0.078	1.822	.01
Slope x speed x individual	2.01	60	0.034	0.780	
Error	6.20	144	0.043		

TABLE VII

SUMMARY OF ANALYSIS OF VARIANCE FOR HORIZONTAL DISTANCE OF HEEL TO HIP AT CONTACT

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	3031.90	287			
Slope	1501.29	2	750.65	227.544	.01
Speed	137.43	2	68.71	20.829	.01
Slope x speed	10.54	4	2.64	0.799	
Individual	447.91	15	29.86	9.052	.01
Slope x individual	226.82	30	7.56	2.292	.01
Speed x individual	113.95	30	3.80	1.151	
Slope x speed x individual	118.91	60	1.98	0.601	
Error	475.04	144	3.30		

TABLE VIII

SUMMARY OF ANALYSIS OF VARIANCE FOR VERTICAL DISTANCE OF HEIGHT OF BODY AT CONTACT TO HEIGHT OF BODY AT TAKE-OFF

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	254.38	287			
Slope	15.59	2	7.80	10.294	.01
Speed	0.28	2	0.14	0.186	
Slope x speed	1.39	4	0.35	0.458	
Individual	22.46	15	1.50	1.977	.05
Slope x individual	38.32	30	1.28	1.686	.05
Speed x individual	17.24	30	0.57	0.758	
Slope x speed x individual	50.03	60	0.83	1.101	
Error	109.07	144	0.76		

TABLE IX

SUMMARY OF ANALYSIS OF VARIANCE FOR VERTICAL DISTANCE OF HEIGHT OF BODY AT CONTACT TO HEIGHT OF BODY AT TEMPORAL MID-NON-SUPPORT

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	424.86	287			
Slope	43.53	2	21.76	18.377	.01
Speed	0.69	2	0.31	0.266	
Slope x speed	1.58	4	0.39	0.333	
Individual	43.58	15	2.91	2.453	.01
Slope x individual	5[illegible].04	30	1.70	1.437	
Speed x individual	[illegible]14	30	0.87	0.736	
Slope x speed x individual	87.84	60	1.46	1.236	
Error	170.53	144	1.18		

TABLE X

SUMMARY OF ANALYSIS OF VARIANCE FOR
BODY ANGLE AT CONTACT TO VERTICAL

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	18361.80	287			
Slope	10662.80	2	5331.39	562.252	.01
Speed	1672.77	2	836.39	88.206	.01
Slope x speed	76.24	4	19.06	2.010	
Individual	2417.54	15	161.17	16.997	.01
Slope x individual	901.92	30	30.06	3.171	.01
Speed x individual	580.36	30	19.35	2.040	.01
Slope x speed x individual	684.75	60	11.41	1.204	
Error	1365.44	144	9.48		

TABLE XI

SUMMARY OF ANALYSIS OF VARIANCE FOR ANGLE OF THE LOWER LEG SEGMENT AT CONTACT TO HORIZONTAL

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	18543.50	287			
Slope	12922.80	2	6461.41	597.743	.01
Speed	585.70	2	292.85	27.091	.01
Slope x speed	92.60	4	23.15	2.142	
Individual	807.86	15	53.86	4.982	.01
Slope x individual	1280.32	30	42.68	3.948	.01
Speed x individual	604.11	30	20.14	1.863	.01
Slope x speed x individual	693.49	60	11.56	1.069	
Error	1556.59	144	10.81		

TABLE XII

SUMMARY OF ANALYSIS OF VARIANCE FOR ANGLE OF THE LOWER LEG SEGMENT AT TAKE-OFF TO HORIZONTAL

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	5735.20	287			
Slope	63.67	2	31.84	3.174	.05
Speed	1900.86	2	950.54	94.769	.01
Slope x speed	6.95	4	1.74	0.173	
Individual	1120.97	15	74.73	7.452	.01
Slope x individual	549.57	30	18.32	1.827	.01
Speed x individual	289.34	30	9.64	0.962	
Slope x speed x individual	359.66	60	5.99	0.598	
Error	1444.17	144	10.03		

TABLE XIII

SUMMARY OF ANALYSIS OF VARIANCE FOR ANGLE OF THE DRIVING THIGH SEGMENT AT TAKE-OFF TO VERTICAL

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	32115.20	287			
Slope	2186.33	2	1093.17	47.360	.01
Speed	20354.00	2	10177.00	440.903	.01
Slope x speed	326.76	3	90.69	3.929	.01
Individual	2583.15	15	172.21	7.461	.01
Slope x individual	1334.87	30	44.50	1.928	.01
Speed x individual	1118.09	30	37.27	1.615	.05
Slope x speed x individual	852.06	60	14.20	0.615	
Error	3323.84	144	23.08		

TABLE XIV

SUMMARY OF ANALYSIS OF VARIANCE FOR
BODY ANGLE AT TAKE-OFF TO VERTICAL

Effect	Sum of Squares	df	Mean Squares	F-ratio	P
Total	17074.90	287			
Slope	10824.80	2	5412.41	563.255	.01
Speed	415.72	2	207.86	21.631	.01
Slope x speed	64.64	4	16.16	1.682	
Individual	2428.49	15	161.90	16.848	.01
Slope x individual	937.29	30	31.24	3.251	.01
Speed x individual	496.47	30	16.55	1.722	.01
Slope x speed x individual	523.80	60	8.73	0.909	
Error	1383.72	144	9.61		

APPENDIX B

TUKEY TEST TABLES

TABLE XV

THE MAGNITUDE AND SIGNIFICANCE OF SLOPE AND SPEED GROUP MEAN DIFFERENCES AS REVEALED BY TUKEY TESTS

Group Mean Differences	Elements of the Running Stride 1	2	3	4	5	6	7
$d_{.05}$	0.9974	0.0468	0.0033	0.0046	0.0062	0.6140	0.2939
$d_{.01}$	1.2415	0.0583	0.0041	0.0058	0.0824	0.7643	0.3659
Horizontal Trials-Uphill Trials	6.2952[a]	-0.1980[a]	0.0087[a]	0.0098[a]	-0.0397	3.1892[a]	-0.0450
Horizontal Trials-Downhill Trials	-1.1952[b]	0.0949[a]	0.0020	-0.0152[a]	0.1733[a]	-2.3841[a]	-0.5146[a]
Uphill Trials-Downhill Trials	-7.4904[a]	0.2929[a]	-0.0067[a]	-0.0249[a]	0.2130[a]	-5.5733[a]	-0.4696[a]
11 ft./sec. Trials-16 ft./sec. Trials	-14.4440[a]	-0.3062[a]	0.0525[a]	-0.0148[a]	0.5943[a]	-1.5949[a]	0.0712
11 ft./sec. Trials-21 ft./sec. Trials	-21.7164[a]	-0.7369[a]	0.0875[a]	-0.0073[a]	0.7716[a]	-1.2869[a]	0.0598
16 ft./sec. Trials-21 ft./sec. Trials	-7.2724[a]	-0.4306[a]	0.0350[a]	0.0075[a]	0.1773[a]	0.3080[a]	-0.0115

[a]Significant at .01 level. [b]Significant at .05 level.

TABLE XV (Continued)

$d_{.05}$	0.3671	1.0403	1.1108	1.0695	1.6232	1.0473
$d_{.01}$	0.4569	1.2949	1.3827	1.3312	2.0204	1.3036

Group Mean Differences	Elements of the Running Stride					
	8	9	10	11	12	13
Horizontal Trials-Uphill Trials	-0.4924[a]	-11.3985[a]	-10.9323[a]	0.7979	-1.8334[b]	-10.1537[a]
Horizontal Trials-Downhill Trials	-0.9521[a]	2.6172[a]	5.1302[a]	-0.3203	4.7083[a]	4.5052[a]
Uphill Trials-Downhill Trials	-0.4597[a]	14.0157[a]	16.0625[a]	-1.1182[b]	6.5417[a]	14.6589[a]
11 ft./sec. Trials-16 ft./sec. Trials	-0.0920	-3.2057[a]	-0.3125	3.2563[a]	-10.8880[a]	-1.5026[a]
11 ft./sec. Trials-21 ft./sec. Trials	-0.1050	-5.8958[a]	-3.1693[a]	6.2917[a]	-20.5807[a]	-2.9427[a]
16 ft./sec. Trials-21 ft./sec. Trials	-0.0130	-2.6901[a]	-2.8568[a]	3.0354[a]	-9.6927[a]	-1.4401[a]

[a]Significant at .01 level.

[b]Significant at .05 level.