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Cinematographic Analysis of the Developmental Stages
of Running in Preschool Boys and Girls

presented by

Joy E. Kiger

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Physical Education and Exercise Science

Crystal F. Branta
Major professor

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CINEMATOGRAPHIC ANALYSIS OF THE DEVELOPMENTAL STAGES OF RUNNING IN PRESCHOOL BOYS AND GIRLS

by

Joy E. Kiger

A DISSERTATION

Submitted to
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Division of Physical Education and Exercise Science
School of Health Education, Counseling Psychology, and Human Performance

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ABSTRACT

CINEMATOGRAPHIC ANALYSIS OF THE DEVELOPMENTAL STAGES OF RUNNING IN PRESCHOOL BOYS AND GIRLS

By

Joy E. Kiger

Motor development researchers have identified age related, but not age dependent, changes for key characteristics observed in developing fundamental skills of children. In the skill of running the key descriptive characteristics are generally synonymous with kinematic variables investigated by age or grade level in biomechanics studies. However, biomechanical analysis of the developmental stages of various fundamental motor skills has yet to be done. This interdisciplinary study was undertaken to explore the potential for using biomechanical research techniques to determine the extent and significance of mechanical differences observed in developing running skill. Its purpose was to identify which specific variables differed among the four developmental stages of running as well as between gender performances. Simultaneous sagittal and frontal view high speed cinematography was used to analyses selected kinematic variables which represented the distinguishing characteristics of the four developmental stages of running. Seven major areas were investigated: (a) running descriptors and selected anthropometric measures; (b) segmental inclination at selected points during the running cycle; (c) distance between the

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downward vertical projection of the body's center of gravity and the foot at touchdown; (d) sequence of peak angular velocity for leg segments; (e) midline-limb segment center of gravity distance at selected points during the running cycle; (f) temporal analysis; and (g) limb segment displacements, both linear and angular. Variables were analyzed for each leg to observe differences between right and left limb actions. Statistical significance for stage effect was obtained for trochanteric height, running velocity, right shank at touchdown, right forearm at humerus maximum backward position, and angular displacement of the right forearm, and for gender effect in the left shank at maximum leg extension. Developmental trends across stages were identified in almost all areas investigated. Symmetrical performance was not expected, but right-left variations were consistently larger among stage two and stage three runners than stage one and four runners. Despite the limited statistical significance for stage effect, the data revealed that the use of biomechanical research techniques to investigate developmental stages holds promise for providing invaluable insight into the development of fundamental motor skills in young children.

To my most inspirational teachers -
my students.

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God gave me a dream;
motivated me to set a goal;
and He kept stimulating me to succeed.*

With perseverance and assistance a dream can be achieved. I would like to take this opportunity to acknowledge those individuals who influenced or assisted with my attempt of a project of this magnitude.

First, to my parents for their love and financial support over the years. Their faith was a great source of strength throughout the struggle.

To the children in the Northmont City Schools, Englewood, Ohio, and particularly the students at Englewood Hills Elementary School. For many years the children were my teachers as much as I was their teacher. They especially stimulated my desire to obtain a deeper understanding of the development of motor skill performance in young children.

To Dr. Nadine Zimmerman and Dr. Sharon Plowman of Northern Illinois University. These two individuals convinced me to seek out the advanced degree and teach teachers as well as young children.

To Dr. Robert Shapiro, (University of Kentucky, formerly at Northern Illinois University) for introducing me to the potential of biomechanics research techniques to investigate motor development questions. His term assignment really did become a dissertation.

To my dissertation committee; Dr. Crystal F. Branta, Chair, Dr. Betsy Becker, Dr. John Haubenstricker, and Dr. V. Dianne Ulibarri,

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with special acknowledgement to Dr. Ulibarri's willingness to provide access to the facilities, equipment, and biomechanics software program. An immense thank you to both Dr. Branta and Dr. Ulibarri for reading all the extra drafts it took to blend the writing styles of the two disciplines.

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To the folks at Movement Arts, Lansing, Michigan, for developing and challenging my martial art skills and for providing quiescence

amid the rigors of academia.

To Susan for assisting with the anthropometric measurements photography and continuous encouragement. Her many long distant calls of support kept me going.

To Jason and Jeffrey for being super photo models and providing amusing study breaks. Your loving "squeezes" were appreciated far more than you will ever realize.

* Paraphrased from Schuler, R. H. (1983). Tough minded faith for tender hearted people (p.24). Nashville, Tenn.: Thomas Neslon.

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Chapter I

Introduction

The development and complexity of coordinated movements, both animal and human, have intrigued researchers for ages. The investigation of movement, however, had been limited to direct observation until the advent of cinematography. Early cinematographic work by Muybridge (1887/1955, 1887/1957) and Marey (1895) established methods for studying movement that continue to expand with advancements in cinematography.

During the 1920's, 1930's, and 1940's child psychologists focused investigative efforts, both observational and cinematographic, on the development of human prehension and locomotion (Bayley, 1935; Gesell, 1928; H. M. Halverson, 1931; McGraw, 1945; Shirley, 1931) and fundamental motor patterns (Guttridge, 1935; Jenkins, 1930; McCaskill & Wellman, 1938; Wellman, 1937). These basic patterns involved locomotor, nonlocomotor, and manipulative movements of preschool and early elementary age children. Major characteristics in the maturation of physical skills were often grouped into `levels,' `phases,' `steps,' or `stages,' by adapting theories from developmental psychology. Espenschade and Eckert (1980) categorized the approaches by these early researchers as descriptive, kinesiological, or neuromuscular.

During the latter part of the 1950's, physical educators specializing in either motor development or biomechanics began to investigate the development of fundamental motor skills in children. These researchers observed that although young children of the same chronological age exhibited a wide variety of skill levels, the development of individual skills progressed in a rather predictable order from initial behaviors to high levels of proficiency. Their work specifically focused on the development of 'normal' fundamental motor skill patterns. These researchers have concentrated on either a battery of skills or on a single skill in their investigations.

Several different approaches have been used by recent investigators in their studies. One approach continued the line of research used in the early studies by establishing achievement or performance scores by age or grade and gender (Frederick, 1977; Keogh, 1965; Morris, Williams, Atwater, & Wilmore, 1982). A second approach involved the categorization of skill performance as "good" or "poor" on the basis of a product score and then looking for the biomechanical differences between the two categories of performance (Beck, 1966; Dittmer, 1962). A third approach involved filming children of selected ages and then looking for biomechanical differences among performances (Brown, 1978; Clouse, 1959; Fortney, 1964, 1980; Mersereau, 1974, 1977). A fourth approach required the filming of numerous children at various ages while they performed fundamental motor skills. These films were then analyzed for qualitative movement characteristics that depicted certain levels or stages of development for each skill (Roberton & L. E. Halverson, 1984a, 1984b; Roberton, Williams, & Langendorfer, 1980; Sapp, 1980; Seefeldt,

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Two different staging methods have emerged from this fourth approach, that of component parts developed by Roberton (1975, 1976, 1977, 1978a, 1978b, 1984) and that of total body configuration developed by Seefeldt et al. (1972) and later adapted by McGlenaghan and Gallahue (1978). Further research using the component parts and the total body configuration approaches has continued to refine and validate the earlier findings (Branta, Haubenstricker, Kiger, & Ulrich, 1984; Fountain, Ulrich, Seefeldt, & Haubenstricker, 1981; L. E. Halverson & Williams, 1985; Haubenstricker, Branta, & Seefeldt, 1983; Haubenstricker, Branta, Ulrich, Brakora, & E-Lotfalian, 1984; Haubenstricker, Seefeldt, & Branta, 1983; Haubenstricker, Seefeldt, Fountain, & Sapp, 1981; S. Miller, Haubenstricker, & Seefeldt, 1977; Roberton, 1982; Roberton & L. E. Halverson, 1984; Roberton, Williams, & Langendorfer, 1980; Way, Haubenstricker, & Seefeldt, 1979). Research using the component parts and total body configuration approaches provides the preschool and elementary school physical educator with detailed information on the qualitative development of fundamental motor skills to complement the quantitative (distance, speed) information already available for age and gender.

Except for the work reported by Branta et al. (1984), Fountain et al. (1981), Glassow, L. E. Halverson, & Rarick (1965), and Haubenstricker et al. (1984) evidence on the relationship between qualitative development and performance scores has been lacking in both the motor development and the biomechanics disciplines. Research results from the Early Childhood Motor Skills Development Study [Early

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Childhood] (1985) provide age percentile rankings in developmental stages for ten fundamental motor skills, as well as percentile rankings for running time, agility time, balance time, and jumping distance for children in the age range 2.5 to 5 years. This eight year, mixed longitudinal study provides unique data for establishing the link between the qualitative and quantitative performance scores. Yet, the link between process and product in the development of children's motor performance needs further research. Roberton (1972), Smoll (1979), and Wickstrom (1975) noted the potential of kinesiological techniques for examining the process-product link in understanding skill development. Garrett (1978) used the term "developmental biomechanics" to designate the use of biomechanical research techniques in the study of skill development. According to Garrett, developmental biomechanics holds promise for fulfilling the need in developmental research not only for further investigating the process of skill development, but also for providing more precise measures than the verbal descriptions of skill development provided in the past. By combining the research efforts of the motor developmentalist and the developmental biomechanist (not to mention the efforts of the child developmentalist, sport psychologist, sociologist, and physiologist), the potential for gaining a more thorough and precise understanding of motor skill development through synergistic research efforts is promising (Garrett, 1978).

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The Research Problem

Research conducted by motor developmentalists and developmental biomechanists on the development of fundamental motor skills, and on running in particular, has been limited to age/grade level or speed differences. For the skill of running, analyses have been limited mostly to leg movements. As a result, a void exists in the data base regarding resultant arm movement patterns and important rotary movements that occur around the vertical axis of the body, as well as the role of these movements in the performance of the maturing skill. Furthermore, biomechanical differences among the identified developmental stages of fundamental motor skills have not been analyzed. With a kinematic analysis, physical educators would be able to ascertain more effectively the significance of the mechanical differences among the identified developmental stages of a skill.

The developmental stages of fundamental motor skills have been shown to be age related but not age dependent. In the case of running, speed also improves with the use of a more mature skill pattern. Previous biomechanical studies of running in children have attributed significant differences in selected kinematic variables to the function of age (Amano, Mizutani, & Hoskawa, 1983; Beck, 1966; Brown, 1978; Clouse, 1959; Dittmer, 1962; Fortney 1964, 1980; Mersereau, 1974, 1977; Smith, 1977). Early motor development research also attributed differences in running speed to age (Carpenter, 1942; Cunningham, 1927; Deach, 1951; Frederick, 1977; Glassow et al., 1965; Glassow & Kruse, 1960; Guttridge, 1939; Jenkins, 1930; McCaskill & Wellman, 1938;

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It was, therefore, the purpose of this study to investigate selected kinematic variables representing the distinguishing characteristics of the developmental stages of running according to Seefeldt et al. (1972). Through the use of simultaneous sagittal and frontal plane high speed filming, the stated concerns and questions relative to arm and leg movement pattern differences among the developmental stages were addressed to provide quantitative information on the qualitative development of running behavior in young children. Such information is needed to verify quantitatively the significance of identified stage pattern differences and to provide base line kinematic data for future research in running stage development. This study focused on the four developmental stages of running as described by Seefeldt et al. (1972). The sequence of these stages has been verified through mixed longitudinal studies (Fountain et al., 1981; Branta et al., 1985; Early Childhood, 1985). The practical application of this running stage sequence was evident in its use in the Test of Gross Motor Development (Ulrich, 1985).

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Terminology

Readers of interdisciplinary studies not familiar with the basic terminology of specific areas of study may have difficulty understanding the nomenclature used. For this reason, terminology used in the current study will be presented at this time. The terminology reflects the nomenclature prevalent in motor development and biomechanics and was compiled from the works of authors in each area of study (Beck, 1966; Clouse, 1959; Dillman, 1975; Dittmer, 1962; Dyson, 1973; Fortney, 1980; Groves & Camaione, 1983; Hay, 1985; Haywood, 1986; Hopper, 1964; James & Brubaker, 1973; Northrip, 1983; Seefeldt, 1974; Seefeldt et al., 1972; Simonian, 1981; Slocum & James, 1968; Wickstrom, 1983).

Motor Development is concerned with describing the underlying processes and the changes in movement behavior that occur over time which reflect the interaction of the human organism with its environment (Hayward, 1986; Wickstrom, 1983). Qualitative analysis in motor development involves the identification of characteristics in the form used for accomplishing a task, as well as the sequence in which various characteristics appear as the skill develops from the first rudimentary attempts to an efficient, mature performance. Quantitative analysis in motor development involves determining the direction, speed, and shape of developmental changes plotted on distance, speed, and acceleration curves. For example, in fundamental motor skills, quantitative analysis involves how fast (speed) a child runs a certain distance or how far (distance) a child may jump or throw or how many times a child can hit a target with an object (accuracy).

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Biomechanics is "concerned with the internal and external forces acting on the human body and the effects produced by these forces" (Hay, 1985, p.2). The science of biomechanics consists of two branches, kinematics and kinetics. Kinematics is concerned with describing the motion of a body or body parts using linear and angular displacements, velocities, and accelerations, without regard for the underlying causes of the movement. Linear kinematics deals with the description of translation or linear motion while angular kinematics deals with rotation or angular motion. Kinetics is concerned with the forces that initiate, alter, and stop the motion of the body or body parts and involves the study of forces and moments. Qualitative analysis in biomechanics, as in motor development, involves visual and recorded observation to obtain descriptions of skill performance. Quantitative kinematic analysis also uses recording techniques and involves the measurement of position in space and calculations of linear and angular displacements, velocities, and accelerations of the body or body parts in question during skill performance. Quantitative kinetic analysis involves the measurement of the external forces that cause and affect the movement of the body or body parts in question during skill performance.

Fundamental Motor Skills are common motor skills with specific patterns that involve two or more body segments and result in the transfer or reception of some external object or of the body itself. Examples of fundamental motor skills include running, jumping, throwing, catching, kicking, punting, skipping, and hopping.

Pattern is an isolated movement which is confined to joints or

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segments too restrictive to be classified as a complete fundamental motor skill, i.e. an underarm pattern.

Stage is a specific level of development in a fundamental motor skill containing certain identifiable characteristics.

Phase is a portion of a stage, such as the preparatory phase, the propulsive phase, or the follow through phase.

Sequence is a series of movements which is highly predictable with reference to the performer and the skill.

Running is a rapid form of locomotion characterized by periods of flight when the body is projected above the support surface alternately by each leg. It consists of a smoothly coordinated, rhythmical series of alternating periods of support and flight.

Running Cycle is from touchdown on one foot until the same foot touches down again. In one running cycle, each leg moves through a drive and recovery interval as the total body passes through two periods of support and two periods of flight.

Running Stride is from foot touchdown (or contact) with the supporting surface until touchdown (or contact) with the supporting surface by the opposite foot.

Support Period is the duration of time the foot is in contact with the supporting surface.

Flight Period is the duration of time when the body is nonsupported.

Touchdown Position is the instant any part of the lead foot touches the supporting surface. Also called contact.

Midsupport Position is the position when the lower leg (shank) is

perpendicular to the running surface.

Takeoff Position is the position where the foot is last observed in contact with the supporting surface.

Maximum Leg Angle is the point at which the hip and knee joints of the support leg reach greatest extension and the concomitant ankle joint reaches greatest plantar flexion.

Minimum Knee Angle is the knee angle of the recovery leg when the foot is nearest the buttocks during the recovery interval.

Maximum Thigh Height is the maximum forward height reached by the thigh segment relative to the horizontal during the recovery interval.

Leg Action is the drive interval plus a recovery interval.

a) Drive Interval is the portion of leg action when the foot is in contact with the supporting surface. It consists of three phases.

1) Foot Strike Phase is the time from touchdown to when the foot is flat on the supporting surface and the joints of the support leg are undergoing flexion.

2) Midsupport Phase is the time from when the foot is completely in contact (flat) with the supporting surface until the heel breaks contact with the supporting surface. During this phase, the actions at the hip and knee joints reverse from flexion to extension and the movement at the ankle joint reverses from dorsiflexion to plantar flexion.

3) Takeoff Phase is the time from when the heel breaks contact with the supporting surface to toe off. The hip and knee joints are undergoing extension and the ankle plantar

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flexion.

b) Recovery Interval is the portion of leg action when the foot is not in contact with the supporting surface. It consists of three phases.

1) Follow Through Phase is the time from takeoff until the thigh reaches its maximum backward movement resulting in the hip joint being at its greatest angle of extension.

2) Forward Swing Phase is the time from when the thigh begins its forward movement until the thigh reaches its maximum height.

3) Foot Descent Phase is the time from when the thigh reaches its maximum height until foot touchdown.

Arm Action is a forward phase plus a backward phase of arm movement.

a) Forward Phase is the time from when the humerus begins its forward angular movement until it stops its forward angular movement.

b) Backward Phase is the time from when the humerus begins its backward angular movement until it stops its backward angular movement.

Linear Distance is the length (magnitude) of a straight line joining two positions, i.e. an initial and final position. For this study linear distance was measured in centimeters.

Linear Displacement is the length (magnitude) and direction of a straight line joining two positions, i.e. an initial and final position. For this study linear displacement was measured in centimeters.

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Linear Speed is the change in distance per unit of time of a body segment or the body's center of gravity. Speed is a scalar quantity which represents magnitude. For this study speed was measured in centimeters per second.

Linear Velocity is the change in displacement per unit of time of a body segment or the body's center of gravity. Velocity is a vector quantity which represents both magnitude and direction. For this study velocity was measured in centimeters per second.

Angular Distance is the magnitude of change in the angle between two positions, i.e. the initial and final positions, of a rotating body or body segment. For this study angular distance was measured in both radians and degrees.

Angular Displacement is the magnitude and direction of change in the angle between the initial and final positions of a rotating body or body segment. For this study angular displacement was measured in both radians and degrees.

Angular Velocity is a change in angular displacement per unit of time. For this study angular velocity was measured in radians per second.

Peak Angular Velocity is the position at which a body segment reaches its greatest angular velocity.

Sequence of Peak Angular Velocity is the order in which the body segments reach their individual peak angular velocity about their respective joint.

Movement in the Sagittal Plane refers to observation of the movement from a camera that is placed so that movement occurring in the

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sagittal plane can be recorded (side view). The sagittal camera is placed perpendicular to movement occurring in the sagittal plane (direction of movement).

Movement in the Frontal Plane refers to observation of the movement from a camera that is placed so that action occurring in the frontal plane can be recorded (front view). The frontal camera is placed perpendicular to movement occurring in the frontal plane.

Trunk Inclination Measurement is measurement of trunk lean from the horizontal to the line that passes from the top of the head to the point located half the distance between the hip joints. The measurement is made counterclockwise relative to the horizontal (see Figure 17, p. 86).

Segmental Inclination is a method of measuring the angle of limb segments in biomechanics. A limb segment is measured counterclockwise relative to the horizontal from the distal end of the segment (see Figure 16, p. 85). Segmental inclinations are then used in interpreting changes in joint angles between body segments.

Midline of the Body. The midline of the body is determined first by locating the midpoint between the two hip joints and the midpoint between the two shoulder joints, then connecting the two midpoints. Measurements were made by drawing a line from, and perpendicular to, the supporting surface up through the midpoint between the hip joints, and continuing to equal head height. The distance was measured in centimeters (see Figure 23, p.93).

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The Research Hypotheses

This study investigated the changes in selected kinematic variables for each of the four developmental stages of running (Seefeldt et al., 1972), with stage one being the least mature form and stage four being the most mature form. The study also identified trends in the selected kinematic variables between boys and girls performing in each of the four developmental stages. One complete running cycle (touchdown of one foot until the same foot touched down again) for each leg was used for analysis. Using a complete cycle for each leg enabled the observation of any differences between right and left limb action in the skill during the film trial selected for analysis.

Kinematic Variables. From the sagittal plane (side view) film the following kinematic variables were studied:

1. The inclinations of the thigh, shank, and foot segments at specified points during one running cycle for each leg.
   a. Leg drive interval: touchdown and takeoff.
   b. Leg recovery interval: minimum knee angle and maximum thigh segment height.
2. The linear and angular displacement of thigh, shank, and foot segments between selected positions during one running cycle for each leg.
   a. Leg drive interval: touchdown to takeoff.
   b. Leg recovery interval: takeoff to minimum knee angle, minimum knee angle to maximum thigh segment height, and maximum thigh segment height to touchdown.

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3. The trunk inclination at touchdown and takeoff during the drive interval for each leg.

4. The sequence of peak angular velocity for leg extension in the drive interval and for leg flexion in the recovery interval during one running cycle for each leg.

5. The horizontal distance between the foot at touchdown and the downward vertical projection of the body's center of gravity for each leg (see Figure 22, p. 92).

6. The temporal relationship of support and flight periods during one running cycle for each leg.

7. The stride length and stride rate during one running cycle for each leg.

8. The inclinations of the humerus and the forearm at maximum forward and maximum backward swing of the humerus.

9. The linear and angular displacement for the humerus and the forearm between maximum forward swing and maximum backswing.

From the frontal plane (front view) film the following kinematic variables were studied:

10. The positions of the centers of gravity of arm and leg segments in relation to the body's midline at selected points during one running cycle for each leg (see Figure 23, p. 93).

    a. Leg drive interval: touchdown and takeoff.

    b. Leg recovery interval: minimum knee angle and maximum thigh segment height.

In addition the following relationships were investigated for each stage of running:

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11. The relationship of stride length to stride rate, stride length to running speed, stride rate to running speed, trochanteric height to running speed, and trochanteric height to stride length.
12. The temporal occurrence between selected positions for each stage of running.
    a. Leg drive interval: touchdown to maximum leg extension and maximum leg extension to takeoff.
    b. Leg recovery interval: takeoff to minimum knee angle, minimum knee angle to maximum thigh segment height, and maximum thigh segment height to touchdown.

Predicted Developmental Trends. Based on review of the qualitative films of running stages filmed at Michigan State University from 1967 through 1976, the following developmental trends were predicted for this study:

1. At touchdown, the inclination of the thigh, relative to the horizontal, will decrease from stage one to stage two, increase from stage two to stage three, and decrease from stage three to stage four. The inclination of the shank and foot, relative to the horizontal, will increase from stage one to stage two, then progressively decrease at stages three and four (see Figure 1).
2. At takeoff, the inclination of the thigh and shank, relative to the horizontal, will decrease from stage one to stage two and from stage three to stage four, but will increase from stage two to stage three. The inclination of the foot, relative to the horizontal, will progressively decrease from stage one through

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Figure 1.
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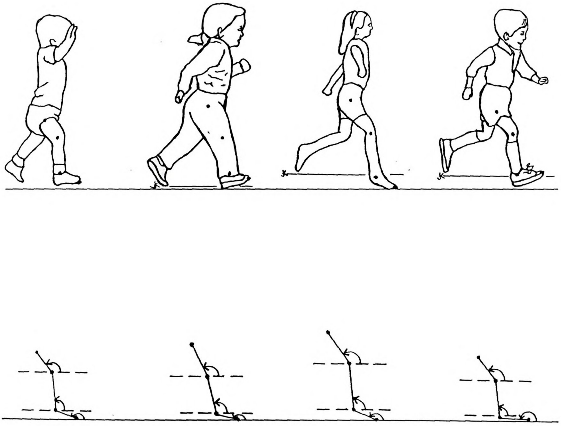

Stage 1 Stage 2 Stage 3 Stage 4

Figure 1. Illustrations of predicted changes in segmental inclinations of the leg at touchdown position.

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three, then increase from stage three to stage four (see Figure 2).

3. At minimum knee angle of the recovery interval, the segmental inclinations of the thigh and shank relative to the horizontal will decrease from stage one through three, then increase from stage three to stage four (see Figure 3).

4. At maximum thigh segment height, the segmental inclination of the thigh, relative to the horizontal, will decrease from stage one through stage three, then increase from stage three to stage four (see Figure 4).

5. The angle of trunk inclination will increase as the stages progress from one to four.

6. The sequence for peak angular velocity of leg extension during the drive interval and of leg flexion during the recovery interval will move from simultaneous occurrence, or non sequential, to sequential occurrence as the stage level increases. The leg extension sequence for the drive interval will follow the order: thigh, shank, and foot, while the leg flexion sequence during the recovery interval will follow the order: shank, thigh, and foot.

7. The horizontal distance between the foot at touchdown position and the downward vertical projection of the body's center of gravity during a running cycle for each leg will decrease as stages increase.

8. During one running cycle for each leg, the time in support will decrease while the time in flight will increase at each successive stage.

9. The stride length and rate, relative to leg length, will increase

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three, then increase from stage three to stage four (see Figure 2).

3. At minimum knee angle of the recovery interval, the segmental inclinations of the thigh and shank relative to the horizontal will decrease from stage one through three, then increase from stage three to stage four (see Figure 3).
4. At maximum thigh segment height, the segmental inclination of the thigh, relative to the horizontal, will decrease from stage one through stage three, then increase from stage three to stage four (see Figure 4).
5. The angle of trunk inclination will increase as the stages progress from one to four.
6. The sequence for peak angular velocity of leg extension during the drive interval and of leg flexion during the recovery interval will move from simultaneous occurrence, or non sequential, to sequential occurrence as the stage level increases. The leg extension sequence for the drive interval will follow the order: thigh, shank, and foot, while the leg flexion sequence during the recovery interval will follow the order: shank, thigh, and foot.
7. The horizontal distance between the foot at touchdown position and the downward vertical projection of the body's center of gravity during a running cycle for each leg will decrease as stages increase.
8. During one running cycle for each leg, the time in support will decrease while the time in flight will increase at each successive stage.
9. The stride length and rate, relative to leg length, will increase

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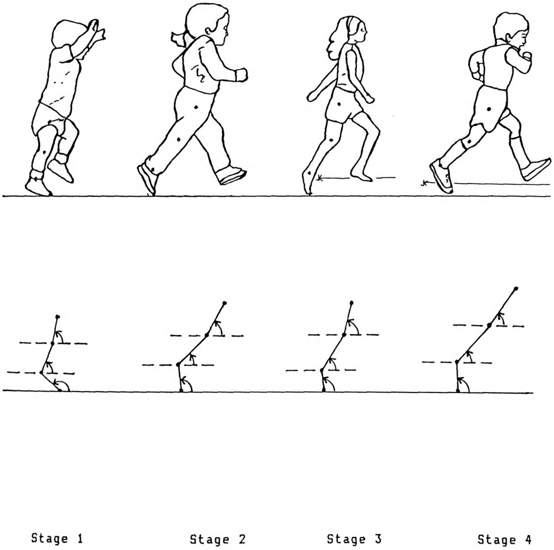

Figure 2. Illustrations of predicted changes in segmental inclinations of the leg at takeoff position.

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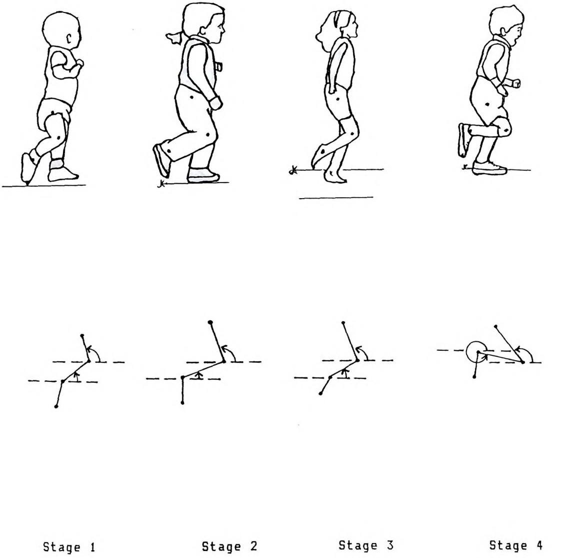

Figure 3. Illustrations of predicted changes in segmental inclinations of the leg at minimum knee angle during the recovery interval.

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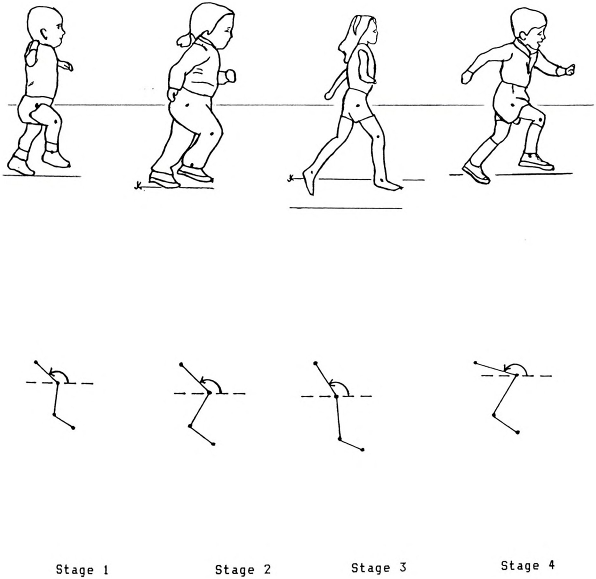

Figure 4. Illustrations of predicted changes in segmental inclinations of the thigh at maximum thigh segment height.

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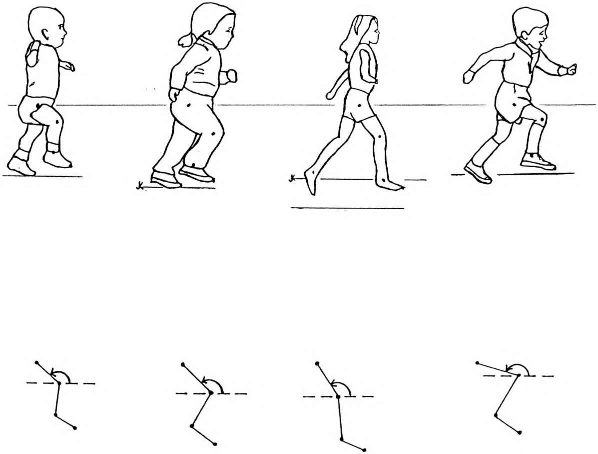

Stage 1 Stage 2 Stage 3 Stage 4

<u>Figure 4</u>. Illustrations of predicted changes in segmental inclinations of the thigh at maximum thigh segment height.

at each successive stage.

10. At maximum forward arm swing, the segmental inclination of the humerus, relative to the horizontal, will decrease from stage one to stage two, and from stage two to stage three, but will increase from stage three to stage four. The inclination of the forearm, relative to the horizontal, will decrease from stage one through stage three, then increase from stage three to stage four (see Figure 5).
11. At maximum backward arm swing, the segmental inclination of the humerus, relative to the horizontal, will decrease from stage one to stage two, increase from stage two to stage three, then decrease from stage three to stage four. The segmental inclination of the forearm relative to the horizontal, will decrease at each successive stage (see Figure 6).
12. The distance between the center of gravity of each limb segment relative to the body's midline will decrease at each successive stage.

Hypotheses. The following hypotheses were examined for this study:

1. Each of the selected kinematic variables will follow the predicted trends, showing significant differences from stage to stage, in the running behavior of young children.
2. There will be no observed differences on each of the selected kinematic variables across stages between boys and girls.

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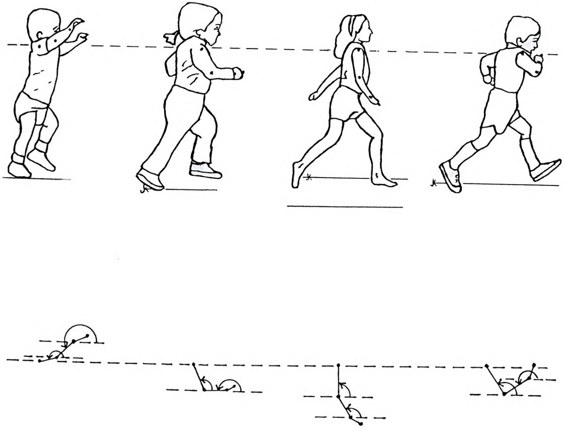

Stage 1 Stage 2 Stage 3 Stage 4

Figure 5. Illustrations of predicted changes in segmental inclinations of the humerus and forearm at maximum forward angular rotation of arm swing.

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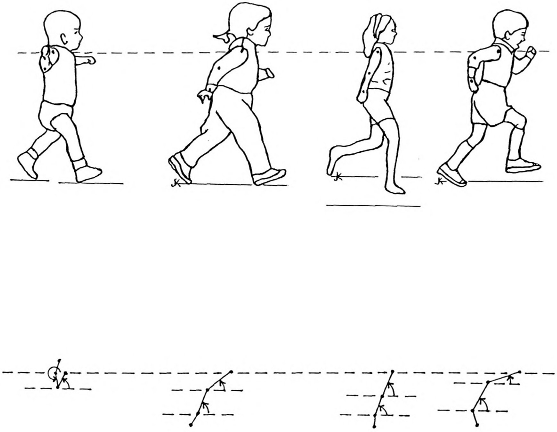

Stage 1 Stage 2 Stage 3 Stage 4

Figure 6. Illustrations of predicted changes in segmental inclinations of the humerus and forearm at maximum backward angular rotation of arm swing.

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The Scope of the Study

The study examined the running gait of preschool aged boys and girls. Each subject was filmed simultaneously by two cameras positioned orthogonally to each other; one camera from the sagittal (side) view, the other from the frontal (front) view. One boy and one girl demonstrating each one of the four classic developmental stages of running (n=8) were selected from an identified potential subject pool of children participating in the Michigan State University Early Childhood Motor Skill Development Program. Additional subjects were selected as needed (i.e. to represent immature stages not demonstrated by subjects in the Early Childhood Program) from siblings of the participants in this program or from other available children. Each subject participated in a single filming session. Selected anthropometric measurements also were taken during this session. Selected film trials were digitized and processed through a biomechanical software program to obtain the necessary linear and angular displacements, velocities, and accelerations for statistical analyses in order to answer the posed research hypotheses.

Limitations

The following limitations were identified for this study:

1. Motor development research studies have traditionally used large numbers of subjects, where biomechanical research studies have traditionally used a small number of subjects. For this study eight

subjects were selected, one boy and one girl for each developmental stage of running. The developmental stages for running as determined by Seefeldt et al. (1972) were ascertained through qualitative film analysis of over 150 children between the ages of 18 months and 8 years of age. These four developmental stages of running have been verified on four occasions (Branta et al., 1984; Branta et al., 1985; Early Childhood, 1985; Fountain et al. 1981). The latest validation (Early Childhood, 1985) involved over 1500 children ages 2.5- to 5.0-years of age. This particular skill stage sequence has been well documented, and no qualitative differences have been noted between boys and girls performing at the various stages. There is general agreement among motor development specialists that developmental stages are age related, but not age dependent, and that boys and girls demonstrate the same degree of identifiable characteristics as they progress through the developmental stages. Thus, the small number of subjects was deemed acceptable for this study.

2. The subjects selected for the study were from an available population of children most of whom were enrolled in a program emphasizing fundamental motor skill development for preschool age children. Program enrollees were from the greater Lansing, Michigan area. Subject selection was further limited in that only children demonstrating the best representative form of a stage during the 1985 fall testing and nearest the modal age for stage, as determined by Early Childhood (1985), were considered for inclusion in the study.
3. The study was limited by the common difficulties encountered in

cinematographic research. These difficulties include error in locating anatomical landmarks when digitizing due to hidden segments and perspective error resulting from body segments positioned at different distances from the cameras.

Assumptions

The study was completed based on two assumptions:

1. That the subjects filmed were representative of normal preschool age boys and girls.
2. That the subjects were developing normally and free from any previous or present handicapping conditions.

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Chapter II

Review of Literature

The study of motor development entails identification of changes in motor behavior that are reflective of an interaction of the human organism with its environment. Identified changes in motor behavior have been classified based on stage theories originating in biology and developmental psychology. To achieve the most effective comprehension of the development of a fundamental motor skill, the investigator needs to: (a) understand developmental stage theory, (b) review completed research on the specific skill of interest, and (c) inquire into other disciplines for related investigations and research techniques that may help advance the interpretation of the skill's development. The investigator who is concerned with the development of a fundamental motor skill also must have a thorough understanding of the mature form of the specific skill being studied. This provides the necessary background against which the developmental progress in the skill can be evaluated (L. E. Halverson, 1966).

The following review of literature reflects the interdisciplinary approach taken by this study. Attention will be given to: (a) the origins of developmental stage theory and its application to motor development; (b) the early studies in motor development; (c) the

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developmental studies of fundamental motor skills; (d) the development of running as studied by specialists in motor development and developmental biomechanics; and (e) the kinematic analysis of mature running form.

Developmental Stage Theory

Developmental staging theory has provided a method of identifying and grouping characteristics or events along a continuum. The following section traces the origins of developmental stage theory and its adaptation to the study of motor skill development.

Biological - Psychological Origins. The emergence of developmental psychology early in the Twentieth Century was the result of increased interest in children and concurrent advances in the scientific method of study. Psychologists began to search for the best ways to educate children (how do they learn?) and to investigate the biological development of the human organism (how do they grow?). The model of developmental used by psychology comes basically from biological sciences (Gardner, 1982). Within the biological discipline, scientists have charted daily progress, identified stages of development, used substances which may control development, and established an overall theoretical framework of an organism's development. This developmental model used by biology views development as making continual differentiation (simple to complex) and integration (a coming together of isolated parts to form a more complex organization) (Gardner, 1982).

The biological model of development and related terminology has been borrowed by many other disciplines, including psychology. It has been applied to the physical development of children with little difficulty. But in the more intangible areas such as cognitive, emotional, and moral growth, the application of biological terminology has been criticized for being too vague, too ambitious, or too restrictive (Gardner, 1982). Questions concerning qualitative versus quantitative developmental descriptions also are raised when attempting to apply biological terminology to these areas.

A major problem lies in the disagreement as to the meaning and use of the term "stages". Brainerd (1978) describes three general applications of the term. First, stages have been used as aesthetic or ideals that do not necessarily refer to any definite or measurable elements in development. Here the term 'stage' is used as a method of eliciting certain images (such as Erickson's (1963) theory of psychosexual development). Second, stages have been used as descriptions of precise and measurable aspects of behavioral development, that is, arbitrarily defined characteristics known to change with age. He notes in the descriptive use of stages that degrees of abstractness may be represented from concrete, detailed descriptions to the isolation of commonalities and patterns present in diverse classes of behavior. Third, stages have been used in an explanatory capacity and must satisfy three criteria to be legitimate explanations of development: (a) the stages must be descriptive of the behaviors that undergo change; (b) they must postulate antecedent variables believed to be responsible for the changes; and (c) there must be ways to measure

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the antecedent variables independently of the behavioral changes.

Although not without criticism, Jean Piaget's stages of cognition (1983), Lawrence Kohlberg's stages of moral development (1963), Sigmund Freud's stages of sexual development (1930/1964), and Erik Erikson's stages of life (1963) may be considered classic examples of stage theories.

Piaget's criteria for stages (hierarchization, structural wholeness, integration, consolidation, and equilibration) have been most widely accepted and used in developmental psychology. Hierarchization refers to a fixed order of succession of the different levels that compose a developmental sequence. That is, the order of the appearance of the levels remains the same. There can be no variation in the described order. Individuals may progress through the sequence at slightly different rates, but the order of succession remains the same. Structural wholeness refers to the individual operating on the same level in several related areas. Integration refers to the accomplishments of a higher stage incorporating those of the lower stage(s). Integration involves the transformation of lower stage elements by restructuring them to form new elements as well as coordinating lower stage elements with completely new elements. Consolidation refers to the continuous gradual evolution of one stage from a previous stage. For a period of time, i.e. during the transition, elements of both stages will be evident. Piaget refers to this as horizontal decalage. And finally, equilibration refers to the process through which the individual develops. Development consists of a series of periods of equilibration followed by disequilibration as an t

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individual moves from a state of stability operating at one stage to a state of instability as the transition occurs to a higher stage. Gesell (1939) used the term reciprocal interweaving to describe the last two characteristics relating the whole process as an ascending spiral of gradual change under the influence of both biological (genetic) and environmental factors.

Essentially, developmental psychologists have strictly adhered to the requirement that all five criteria be met for proposed stage theories to be accepted as an explanation for development. However, this rigid thinking has come under criticism. Brainerd (1978) questions the explanatory value of Piaget's stages of cognitive development. He believes that they are descriptive rather than explanatory in nature since the antecedent variables leading to behavioral changes cannot be measured separately. The concepts of invariant or irreversible sequencing has been questioned by Holstein (1976) and Kurtines and Greif (1974) in reviewing the work of Kohlberg's (1963) development of moral thought. Kurtines and Greif (1974) also question the qualitative differences in the hierarchical stages proposed by Kohlberg. In response to criticisms about the limitations of the definitions of stage criteria, Piaget (1960) himself replied that the five criteria are in reality degrees of the possible structuralization of stages. The five criteria presented represent what Piaget found in the field (versus the laboratory) setting where "stages" are most evident. In reality, whether or not all five criteria are used in a developmental stage theory is up to the individual proposing the theory. Therefore the usefulness of stages can be generalized to a variety of fields.

Stage Theory Applied to Motor Development. Stage theory in developmental psychology gave rise to the use of stage theory in motor skill development. This is logical since many of the early developmental psychology studies used motor skills to demonstrate the existence of sequences in development (Ames, 1937; Burnside, 1927; Gesell, 1946; McGraw, 1943; Shirley, 1931). However, the use of the term "stage" in motor development has been confusing. Without the theoretical background the term stage could be interchanged with descriptions such as "type", "phase", "pattern", or "steps" to describe how a child might react in certain environmental situations or to describe a series of differentiated qualities which appear in a predictable sequence.

Motor stages have been identified through extensive observation, both direct and cinematographic. In a descriptive sense, the focus of early motor development studies varied considerably, yet all were interested in the mechanisms, form and function of movement. For example, H. M. Halverson (1931) focused on what changes occurred; Shirley (1931) concentrated on the order of the changes that occurred; McCaskill and Wellman (1938) attended to the identification, ordering, and quantification of tasks; and Godfrey and Kephart (1969) prepared a check list for elements of a mature performance. In more recent work, investigators have concentrated on the qualitative changes in form that occur during motor skill development (Roberton, 1975, 1982; Roberton & L. E. Halverson, 1984a, 1984b; Seefeldt et al. 1972; Seefeldt & Haubenstricker, 1982).

In a theoretical sense, stage theory refers to the presumptive

structures underlying movement. That is, the underlying neural development directing the changes observed in motor development (Roberton, 1977, 1978). And, according to Wohlwill (1973), the strength of developmental stages comes from their power to demonstrate that each step evolved from the preceding one. The use of stage theory in this Piagetian context is evident in some of the studies previously mentioned (Ames, 1937; Gesell, 1946; McGraw, 1943; and Seefeldt et al., 1972).

Another point of possible confusion in the use of 'stages' in motor development occurs with the concepts of intraskill and interskill development. Interskill stage sequencing involves the developmental ordering of several related tasks. Shirley's (1931) stages of locomotion are an example of interskill staging. Such stages have been related to age ordering. Intraskill staging involves the development of a single skill. The work of H. M. Halverson (1931), Roberton (1975), Roberton & L. E. Halverson (1984a, 1984b), Seefeldt et al. (1972), Seefeldt & Haubenstricker (1982), and Wild (1938) are examples of intraskill staging.

Early Studies of Motor Development

Interest and research in the motor development of children date back several decades. Child psychologists were responsible for much of this early research as they attended to the normal mental and physical development of children. Gesell (1929, 1948) charted normal ontogenic behavior from birth to age 10. Shirley (1931) observed 25 babies through the first 2 years of their lives. Bayley (1935) followed the

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development of over 40 infants from the age of one month to 36 months. McGraw (1935) investigated selected behavior patterns in growing infants through a detailed 2-year study of fraternal twins. In general, these early studies yielded extensive information on the development of upright locomotion revealing that the process was very orderly, yet highly individualized.

During this same time period another group of investigators began examining motor skill achievement separate from mental development. Cunningham (1927) tested the motor achievements of approximately 100 children ranging in age from 12 to 42 months. Children were tested on their birthday and 6 months thereafter in an attempt to establish performance norms for test items of gross motor coordination. Jenkins (1930) tested three hundred 5-, 6-, and 7-year olds to establish standards of performance on nine different motor tasks. Time, distance, and accuracy measurements were gathered. McCaskill and Wellman (1938) studied motor skills in preschool age children (2 to 6 years) to determine the developmental stage, sequence of development, interrelationships among skills, and gender differences in scores. Scores were assigned according to the difficulty of execution based on the percentage of children who accomplished the tasks. In a combination survey of 1,973 children and a one year follow up study of 9 children, Guttridge (1939) examined the motor skill achievements of young children between the ages of 2 and 7 years. Achievements were based on performance scores, teacher ratings, and observation reports.

These multiple skill studies investigated what were considered the common activities of children within the age range of 1 to 7 years.

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Quantitative measures (time, distance, and accuracy scores) were gathered on skills such as running, hopping, skipping, jumping, throwing, catching, kicking, and ball bouncing. Although achievements, in general, were based on performance product scores, McCaskill and Wellman (1938) noted differences in skill development, sequence of individual skill development, order of appearance of skills, and performance variability within any one age group. With few exceptions, significant gains were found as age increased, but McCaskill and Wellman (1938) indicated very little differences between the two oldest groups in their study (5- and 6-year- olds). Up to 1940, only Wild (1938) centered complete attention on the actual development of a single fundamental motor skill in order to identify age characteristics for that skill. All studies made comparisons of age/grade and gender.

For most of the next two and a half decades further investigations into motor skill achievement and development of young children were noticeably absent from the research literature. The few studies that were conducted generally dealt with the development of measurement scales for skill performance of elementary school children (Carpenter, 1942; Johnson, 1962; Latchaw, 1952) or compared physical growth/ biological maturity with performance proficiency in certain gross motor activities (Seils, 1951). Glassow and Kruse (1960) observed motor skill achievement in girls ages 6 to 14 years on the standing broad jump (distance), the 30-yard run (speed), and throwing ability (velocity). Trends were noted on the basis of performance scores and demonstrated that children tend to remain in the same relative position within a group throughout the elementary school years. Glassow, L. E. Halverson,

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and Rarick (1965) reported the results of a 6-year study of children in grades 1 through 6. This 1965 study was unique in that it investigated skill development in terms of performance scores, quality of skill coordination, physical fitness, and strength measures in both a traditional and a vigorous activity type physical education program. This was one of the first research attempts to link the quality of a skill (form) with the resulting performance scores. Improvements with age were noted on both the qualitative and quantitative measurements of the skills under investigation.

The work by Deach (1951) was the first study since Wild's (1938) to focus completely on skill pattern development. Deach investigated the development of discrete performance patterns in children 2- through 6-years of age for selected skills (throwing, catching, kicking, striking, and ball bouncing). This investigator examined the course of development in terms of mature adult performances in the selected skills. Deach's investigation was limited to a small cross-sectional study, but the results indicated development progressing from simple arm and leg actions to integrated total body coordinations.

From the late 1950's through the early 1970's, interest in motor skill development research began to expand. Physical educators specializing in biomechanics were examining kinematic and kinetic differences in developing skills. These studies analyzed skills either by age/grade and gender levels (Brown, 1978; Clouse, 1959; Fortney, 1964, 1980; Mersereau, 1974, 1977; Smith, 1977) or by "good" and "poor" skill levels on the basis of a performance measurement (Beck, 1966;

Dittmer, 1962). During this same time period, physical educators specializing in motor development made use of cinematography to collect extensive data for descriptive studies of skill development. Examples of research using these film sources include the studies on jumping by Hellebrandt, Rarick, Glassow, and Carns (1960), throwing by Roberton (1975), fundamental motor skills by Seefeldt et al. (1972), and galloping by Sapp (1980). These film studies also produced two methods of staging motor skill development. One method, the component parts method, investigated sequential development of body parts separately (i.e. legs, pelvis, trunk, arms) for various fundamental motor skills (Roberton, 1975; Roberton & L. E. Halverson, 1984a, 1984b). The other method, the total body configuration method, identified distinguishing characteristics of a composite performance so that they were easily observed by visual inspection (Seefeldt et al. 1972; Seefeldt & Haubenstricker, 1982). This latter approach was later adopted by McGlenaghan and Gallahue (1978) and Stewart (1980). These studies will be discussed in more detail in the remaining portions of this chapter.

Studies of Developmental Stages in Fundamental Motor Skills

Early studies in child development demonstrated that children follow a predictable sequence in obtaining proficiency in motor skills (Gesell, 1929; McGraw, 1935). The process of determining stages in fundamental motor skills serves as a means of synthesizing and simplifying the complexities of underlying neurophysiological processes and the resulting movements that change over time. Such identification

of specific pattern changes in the phases of a developing motor skill provides the researcher and teacher with a basis for comparing a child's progress in acquiring mature motor patterns as well as for planning instructional strategies for learning and remediating motor skills.

Currently two schools of thought have emerged in the staging of fundamental motor skills: component part staging (Roberton, 1975, 1976, 1977, 1984); and total body configuration staging (Seefeldt et al., 1972; Seefeldt & Haubenstricker, 1982). The component part approach to staging fundamental motor skill development, when first proposed by Roberton (1976), attempted to adhere to the Piagetian criteria for staging, particularly Piaget's criteria for universal and invariant sequences. Roberton noted in her original work that mature performance of various parts of the body seemed to develop at different rates. Developmental stages were then proposed for various parts of the body (arm, trunk, pelvis, legs) as a skill was performed. The sequences were accepted only if all subjects demonstrated the stages in the proposed order. Any variation could only be to adjacent stages. Roberton (1982) has since given consideration to an alternative stage model, a population or probability stage model. This new model for developmental stages, while preserving the ordered regularity of spatio-temporal transformations that occur in motor skill development, permits greater flexibility than the classic Piagetian model.

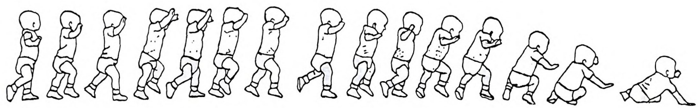
The total body configuration approach to staging fundamental motor skills defines stages based on observation to determine a comprehensive series of movements exhibited to accomplish a specific task (Seefeldt et al., 1972). Work on the total body configuration approach to staging

fundamental motor skills began in the late 1960's. Through extensive qualitative film analyses and by viewing movement as a biomechanical phenomenon, joint actions were identified, ordered, and classified to determine the complete movement series used by children to accomplish certain tasks. Stages were defined when a series of movements demonstrated sufficient commonality as a general phenomenon during children's skill performance. An abrupt change in the positioning of one or more body segments or limbs in relation to previous position depicted the transference from one stage to a higher stage. The change from one stage to a higher level stage resulted in more proficient performance of the task by allowing for a single or combination of mechanical improvements to occur: (a) creating an improved positioning of the body for greater force production; (b) allowing a more extensive range of movement around force producing joints; (c) increasing the number of joints involved in the power train; and (d) permitting less interruption and greater flow to the total movement (Seefeldt & Haubenstricker, 1982). Recognizing that not all the parts of a skill mature at the same rate, there is sufficient identity among the various elements of the skill so that a total configuration description becomes a practical method of describing a task's development. This approach to the staging of fundamental motor skills accepts omissions and reversals as a reality that does not invalidate the stage sequence. The utility of the stage sequence lies in its ability to predict movement characteristics in the majority of the performers, accepting that a child who deviates from the sequence will not cause the invalidation of the sequence. The developmental stages proposed by Seefeldt et al.

(1972) and subsequent staging research conducted at Michigan State University have been further studied and verified by Branta et al. (1984), Branta et al. (1985), Early Childhood (1985), Fountain et al. (1981), Haubenstricker, Branta, & Seefeldt (1983), Haubenstricker & Seefeldt (1977), Haubenstricker, Seefeldt, & Branta (1983), Haubenstricker et al. (1981), Lerner (1975), S. Miller et al. (1977), and Way et al. (1979).

The Development of Running Form

Running is a vigorous form of locomotion, is an outgrowth of walking, and is characterized by distinguishable alternating periods of flight and single foot support. Initial running patterns may actually occur prior to nonsupported walking in response to maintaining balance while trying to move (Broer, 1973). Figure 7 illustrates the extreme high guard arm position and short, choppy steps, of early attempts at running. The first intentional attempts at running usually appear around 18 months of age and represent a modified walk since a flight period is not truly evident. By about 2 years of age, children have gained enough balance and body control to exhibit a truer form of running (Espenshade & Eckert, 1980). As development continues, the width of the stance narrows, there is less toeing out, and the rhythm of the run becomes smoother. By the time children enter kindergarten, they have developed reasonably good running skill and understand what it means to run as fast as possible (Wickstrom, 1983). Research by Seefeldt & Haubenstricker (1982) and Early Childhood (1985) support



<u>Figure 7</u>. Initial attempt at running characterized by extreme high guard position of the arms and short, choppy steps without a true flight period.

later in this chapter.)

Since the late 1950's, research efforts on the development of fundamental motor skills have focused on the qualitative changes that parallel the quantitative trends. A review of the literature revealed 22 studies that either dealt directly with, or included, the development of running in children. These studies are summarized in Table 1. Fourteen of the 21 studies can be generally categorized as what Roberton (1972), Smoll (1982), and Wickstrom (1975) have referred to as developmental kinesiology investigations. The more current term is developmental biomechanics (Garrett, 1979). The biomechanical investigations assessed differences in kinematic and kinetic variables between children of differing age and gender groups. The sequence of appearance of developmental stages of running was investigated in 8 of the 21 studies. Children within the age ranges of 18 months to 8 years were investigated in 15 of the 21 studies. Subjects within the age range of 5 to 11 years were investigated in six of the 21 studies. One study investigated 3- to 10-year olds and one study investigated children aged 14 to 67 months. Eight of the 21 studies involved cross-sectional investigations, while 14 of the 21 studies involved longitudinal and mixed longitudinal research spanning from 4 months to 8 years.

Data on performance differences between boys and girls in the development of running skill are sparse. Only 12 of the 21 studies reviewed involve comparison of boys and girls performances. Glassow et al. (1965) and Amano et al. (1983) reported no difference in running between boys and girls. Atwater et al. (1981) stated that few gender

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Table 1

Summary of Studies on the Development of Running in Children.

	COMPONENTS OF STUDY								
RESEARCHER(S)	Kinematic	Kinetic	Stage	Gender	Age (yrs)	Grade	Cross-sectional	Longi-tudinal	Mixed Longi-tudinal
Amano, Mizutani, & Hoshikawa, 1983	X			M-F	4-7			4 yrs.	
Atwater, Morris, Williams, & Wilmore, 1981	X			M-F	3-6		X		
Beck, 1966	X			M		1,3,5 2,4,6		2 yrs.	
Branta, Haubenstricker, Kiger, & Ulrich, 1984			X	M-F	2.5-5.0				3 yrs.
Branta, Kiger, & Yager, 1985			X	M-F	2.5-5.0				3 yrs.
Brown, 1978	X[a]			F		P,K,2,5	X		
Clouse, 1959	X			M	1.2-4.9			8 mos.	
Dittmer, 1962	X			F	6.0-10			5 yrs.	
Early Childhood, 1985			X[b]	M-F	2.5-5.0				8 yrs.
Fortney, 1964	X			M		2-6		4 yrs.	
Fortney, 1980	X	X		M-F	2,4,6		X		
Fountain, Ulrich, Seefeldt, & Haubenstricker, 1981			X[b]	M-F	2.5-5.0				3 yrs,
Glassow, L.E. Halverson, & Rarick, 1965	X[b]			M-F		1,3,5		2 yrs.	
Learner, 1975			X[b]	M-F	3.0-5.0		X		
Mersereau, 1974	X	X		F	1.9-2.08			4 mos.	
Mersereau, 1977		X[b]		F	2.5-5.5		X		
S. Miller, Haubenstricker, & Seefeldt, 1977			X[b]	M-F	2.5-5.0				1 yr.
Miyamaru, 1976	X			M	2.0-6.0		X		
Seefeldt, Reuschlein, & Vogel, 1972			X[b]	M-F	1.5-8.9		X		
Smith, 1977	X			M-F	5.0-12			5.5-11 yrs.	
Vilchkovsky, Oreshcuk, & Shpitalny, 1973	X			M-F	3.0-7.0		X		
Way, Haubenstricker, & Seefeldt, 1979			X[b]	M-F	6.0-8.9		X		

a = Also included Fourier analysis.

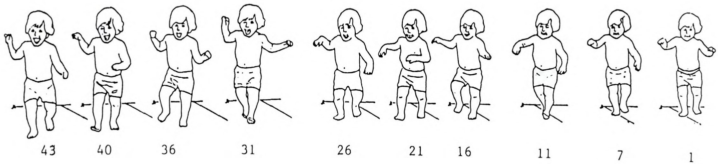
b = Other fundamental motor skills also tested

differences emerged among 3- to 6-year-olds studied with velocity significantly related to height and leg length for the youngest girls. Vilchkovsky et al. (1973) reported only that boys performed better than girls at all ages on running speed. Fortney (1980) noted significant gender differences in four kinematic variables: (a) the joint angle of the swing hip (at touchdown, midsupport, and takeoff), (b) peak angular velocity of flexion of the swing hip, (c) the joint angle of the swing knee, and (d) the range of motion of the swing hip. In the studies investigating the developmental stages of running in children, boys and girls progress through the running stages in the same order, but at each age level reported, the boys in general used a more mature running stage than the girls (Branta et al. 1984; Branta et al. 1985; Early Childhood, 1985; Fountain et al. 1981; Learner, 1975; S. Miller et al. 1977; Way et al. 1979).

Developmental Stages of Running. Developmental stages for running were first proposed by Seefeldt et al. (1972). Subsquently, McGlenaghan and Gallahue (1978) proposed a three-stage sequence of running based on the fundamental sequence proposed by Seefeldt et al. (1972). Drawing upon the earlier investigations of Seefeldt et al. (1972) and Wickstrom (1983), Roberton and L. E. Halverson (1984) hypothesized a developmental sequence of running that involves three steps for the leg action and four steps for the arm action components.

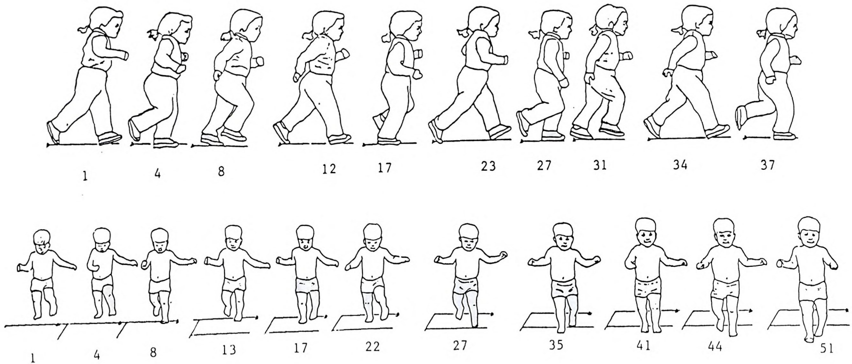
The sequence of developmental stages for running proposed by Seefeldt et al. (1972) has been verified through cross-sectional and mixed longitudinal studies (Branta et al., 1984; Branta et al., 1985;

Early Childhood, 1985; Fountain et al., 1981; Learner, 1975; S. Miller et al., 1977; Way et al., 1979). The four stages of running are illustrated in Figures 8 through 11. In the skill of running the children use more mature running patterns as they increase in age, with boys generally using a more mature pattern at each age level. Seefeldt and Haubenstricker (1982) reported that mature (stage 4) running form was demonstrated by 60% of the boys at age 4 and by 60% of the girls at age 5.5 years. A mixed longitudinal study of the motor skill development in young children ages 2.5 to 5.0 years was begun at Michigan State University in 1978. Data from this study have been analyzed on four occasions over the past 8 years (Branta et al., 1984; Branta et al., 1985; Early Childhood, 1985; and Fountain et al., 1981). Figure 12 illustrates the appearance of the stages as indicated in the analyses completed by Fountain et al. (1981) and Early Childhood (1985). The latest analysis (Early Childhood, 1985) of these data has provided performance standards for each stage by age and gender, mean 30-yard run times and speeds, percentile ranks for running performance by stage, age, and gender, percentile ranks for 30-yard run time by age and gender, and mean run times and speeds by stage, age, and gender. Tables for these data are located in Appendix A. The data show that at age 4 over 50% of the boys are using a mature running form (stage 4) and at age 5 over 50% of the girls were using a mature running form. Mean 30-yard run times and speeds show a decrease in time and increase in speed with progression in stage level and age for both boys and girls.



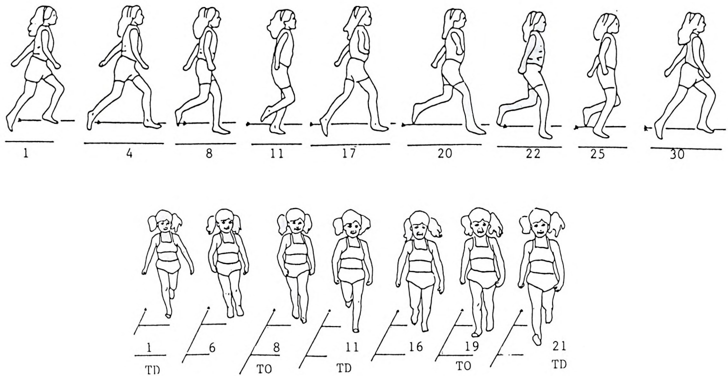
Stage 1. The arms are extended sideward at shoulder height (high-guard position). The stride is short, and of shoulder width. The surface contact is made with the entire foot, simultaneously. Little knee flexion is seen. The feet remain near the surface at all times.

Figure 8. Description (Seefeldt, Reuschlein, & Vogel, 1972) and film tracing of stage one run. Numbers indicate film frame.



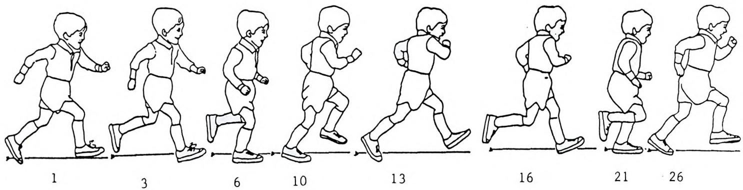
Stage 2. Arm are carried at "middle guard" (waist height), the stride is longer and approaches the midsagittal line. Contact is usually with the entire foot striking the surface simultaneously. Greater knee flexion is noted in the restraining phase. The swing leg is flexed and the movement of the legs becomes anterior-posterior.

Figure 9. Description (Seefeldt, Reuschlein, & Vogel, 1972) and film tracing of stage two run. Numbers indicate film frame.



Stage 3. The arms are no longer used primarily for balance. Arms are carried below waist level and may flex and assume a counter-rotary action. The foot contact is "heel-toe". Stride length increases and both feet move along a mid-sagittal line. The swing leg flexion may be as great as 90 degrees.

Figure 10. Description (Seefeldt, Reuschlein, & Vogel, 1972) and film tracing of stage three run. Numbers indicate film frame.



Stage 4. Foot contact is heel-toe at slow or modest velocities but may be entirely on the metatarsal arch during sprint running. Arm action is in direct opposition to leg action. Knee flexion is used to maintain the momentum during the support phase. The swing leg may flex until it is nearly in contact with the buttocks during its recovery phase.

Figure 11. Description (Seefeldt, Reuschlein, & Vogel, 1972) and film tracing of stage four run. Numbers indicate film frame.

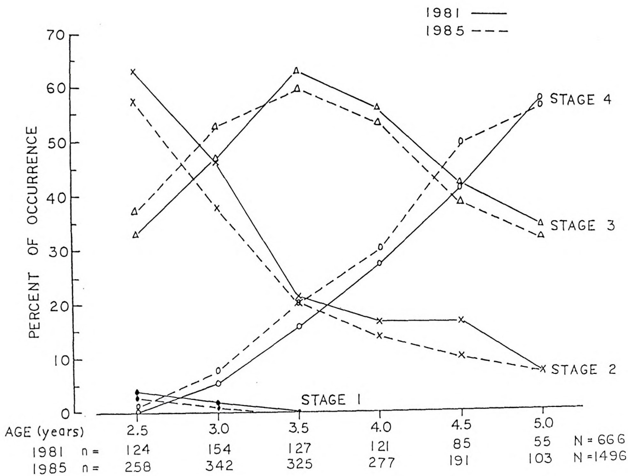


Figure 12. Appearance of the developmental stages of running in preschool age children, independent of gender. Fountain, Ulrich, Seefeldt, & Haubenstricker (1981) and Early Childhood Motor Skills Development Study (1985).

Developmental Biomechanical Studies of Running. Biomechanists interested in skill development have studied running in children. Of the longitudinal, developmental biomechanical research on running reviewed, two studies initially classified children as "good" or "poor" runners based on running speed prior to a kinematic analysis (Dittmer, 1962; Fortney, 1964). Both the "good" and "poor" runners made improvements during the time period they were studied, with the "good" runners consistently making greater gains than the "poor" runners. Regardless of initial classification, the subjects in these two studies tended to maintain the same rankings in relation to their peers each time the running speeds were compared. Several investigations that encompassed preschool and elementary age children found significant age contrasts in kinematic parameters of running. Brown (1978), Fortney (1980), and Vilchkovsky et al. (1973) all reported significant differences between their youngest subjects (2- and 3-year olds) and their oldest subjects (4- to 10-year olds). Despite the use of different age and gender groups, various research emphases, and diverse approaches among the biomechanical studies reviewed, the developmental trends discussed below emerged as age increased.

Increases in stride length and stride rate were accompanied by decreases in support time and increases in flight time for the developing runner. Clouse's (1959) subjects showed increases in stride length both in absolute distance and in relation to extremity length. Beck (1966) attributed the increases in horizontal displacement to an increase in stride length and to the relative increase in percent of time in flight and decrease in percent of time in support for each

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stride. The same trends observed by Beck and Clouse were noted by Amano et al. (1983), Brown (1978), Dittmer (1962), Glassow et al. (1965), Mersereau (1974), Miyamaru (1976), and Smith (1977). Vilchkovsky et al. (1973) also noted that support and flight time were nearly equal in their 7-year-old subjects. However, Atwater et al. (1981), Miyamaru (1976), and Smith (1977) found that as stride length increased, stride rate tended to remain the same or to decrease slightly. Smith (1977) indicated that children did not perform in the same manner as adults. The latter showed increases in both stride length and stride rate up to a certain speed, then further improvement in speed, to a point, would be accomplished only by increases in stride rate.

In examining the development of leg action during the recovery interval, two distinct trends were evident with advancing age and skill: (a) an increase in knee flexion resulted in the foot being carried closer to the buttock and (b) an increase in maximum thigh segment height relative to horizontal. Both trends were found by Brown (1978), Clouse (1959), Fortney (1964), Glassow et al. (1965), and Miyamaru (1976). Clouse (1959) and Dittmer (1962) also observed an increase in the speed at which the thigh moved forward as age advanced and skill level improved.

Two developmental trends associated with the drive interval were noted with increase in skill level and age: (a) a decrease in the distance between the forward foot at touchdown and the downward vertical projection of the body's center of gravity; and (b) an increase in the extension of the leg joints at takeoff. Dittmer (1962) noted the decrease in the distance between the forward foot at touchdown and the

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downward vertical projection of the body's center of gravity among the grade school subjects; whereas, Mersereau (1974) noted just the opposite trend among infants. An increase in leg extension as well as the joint angle and joint angular velocity at takeoff was found by Clouse (1959), Dittmer (1962), Fortney (1980), and Miyamaru (1976). Differences were generally small, but developmental trends also were noted in the joint angles and the joint angular velocities of the hip, knee, and ankle at touchdown and midsupport (Brown, 1978; Clouse, 1959; Dittmer, 1962; Fortney, 1980; Miyamaru, 1976). Fortney (1980) examined the sequence of occurrence of peak angular velocities of joint extension in the support leg and joint flexion in the recovery leg in children. For joint flexion during the recovery interval, peak angular velocity occurred in the predominant order of knee, hip, and ankle. For joint extension during the drive interval, the sequence occurred in the order of hip, knee, and ankle. Fortney found the total transfer of peak angular velocity to follow the summation of forces beginning with flexion of the knee, then flexion of the hip of the swing leg during its recovery interval, followed by extension of the hip, then knee, and finally the ankle of the support leg during its drive interval. This sequence of the transfer of peak angular velocity was common among the 4- and 6-year-olds in the study.

The path of the body's center of gravity created a wavelike pattern in the sagittal plane of the developing runner just as it did in the mature runner. Beck (1966) found that both the horizontal and vertical displacements of the center of gravity increased with age, the greatest gain being in the horizontal displacement. Clouse (1959) found similar

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results to Beck's (1966) and also noted less vertical fluctuation of the body's center of gravity, relative to the horizontal distance of the stride. The reduced vertical fluctuation was evident as well as an absolute increase in stride length, relative to leg length, with advancing age and skill level. Clouse also noted that with increased age the point where the body's center of gravity reached its highest point during a running stride moved from the center of the support period for the younger group to the center of the flight period for the older group. All the biomechanical studies indicated that, with an increase in age, either an increase in horizontal displacement or horizontal velocity (speed) of the body's center of gravity occurred.

Analysis of development of arm action in running is lacking in the literature. Mersereau (1974) mentioned an increase in elbow extension for one of her subjects between the age of 22 months and 25 months. In a later study, Mersereau (1977) mentioned changes occurring in arm movement with skill maturation in reference to a possible explanation for differences between 3- and 4-year-olds in total body kinetic energy attributed to leg and thigh segments. Miyamaru (1976) found an increase in the range of motion of the arm swing with increasing age, while the angle of elbow flexion decreased.

Table 2 summarizes the major developmental biomechanical studies on the skill of running in children. The characteristics noted are based on the factors involved in good or mature running form as described by Dillman (1975) and Wickstrom (1983).

Table

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Table 2

Summary of Major Studies on Biomechanics of Running in Children.

Developmental Characteristics of Good Running Form - Based on Dillman (1975) & Wickstrom (1983)	Clouse, 1959	Dittmer, 1962	Fortney, 1964	Glassow et al., 1965	Beck, 1966	Vilchkovsky et al., 1973	Mersereau, 1974	Miyamaru, 1976	Mersereau, 1977	Smith, 1977	Brown, 1978	Fortney, 1980	Atwater, et al., 1981	Amano et al., 1983
Increase in stride length	+	+		+	+		+	+		+	+	+	+	+
Decrease in support time		+		+	+	+	+	+		+	+			
Decrease in vertical displacement of body	+				+									
Increase in leg extension at takeoff	+	+						+				+		
Increase in knee flexion during recovery	+	+	+	+				+			+	+		
Increase in maximum thigh height during recovery	+		+	+				+			+			
Decrease in distance foot is ahead of c.o.g. at touchdown		+					−							
Sequential backward rotation of leg segments just prior to touchdown														
Thigh of recovery leg swings forward faster	+	+												
Increase in effective use of arms								+	+					
Increase in horizontal velocity (run speed)	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Other									c		b	a c		

a. Sequence of peak angular velocity
b. Harmonic analysis
c. Kinetic analysis

+ = agrees with
− = disagrees with

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The Mature Running Form

Mature running is not only a beautiful skill, but an exciting one to observe. Running can be considered a simple skill because it is an instinctive and natural activity. At the same time it is a difficult skill when considering its mechanical complexity because, in essence, all body parts are moving simultaneously (Dyson, 1973; James & Brubaker, 1973). Although running is considered one of the most common forms of locomotion, the efficient, mature form of the skill does not come naturally. Efficient running form must be learned. No two people run precisely the same way due to various inherited and developmental factors such as posture, anatomical structure, body proportions, strength, training, as well as physiological and psychological factors. Despite the many variables that affect running, efficient running requires the smooth coordination of the entire body. Moreover, certain characteristics of running follow a predictable sequence (James & Brubaker, 1972, 1973). Evidence of the interest in studying human locomotion can be found among the early works of Muybridge (1887/1955, 1887/1957) and Marey (1895). The advent of high speed cinematography provided the opportunity to examine the mechanical complexities of movement. Fenn's (1930, 1931) pioneer efforts in the use of cinematography have become classic studies on the skill of running. Fenn's findings provided a basis for research on both the mature and the developing skill of running.

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Components of the Running Cycle. Running is defined as a rapid form of locomotion characterized by brief periods of flight where the body is projected above the ground alternately by each leg (Dillman, 1975; Fortney, 1980; James & Brubaker, 1972, 1973). Running is a cyclic skill, meaning the same characteristic actions are repeated to create a rhythmical method of locomotion on level surfaces. For the purpose of movement analysis, it is more convenient to consider the various parts that constitute the running cycle, due to the mechanical complexity of the skill. As long as it is repeated, the running cycle can start anywhere. For the purpose of this study the running cycle begins when one foot touches down, or makes first contact with the supporting surface, and is completed when the same foot touches down again. A running cycle contains two strides (or steps), each consisting of a drive interval and a recovery interval. The drive and recovery intervals are further broken down into three phases each (James & Brubaker, 1971, 1973; Slocum & James, 1968). Each phase of the drive and recovery intervals will be examined separately.

The drive interval consists of the foot strike, midsupport, and takeoff phases. The foot strike phase begins the instant any part of the foot touches the support surface and continues until the entire foot is in full contact with the support surface. Flexion occurs at the hip and knee joints with dorsiflexion at the ankle joint during the foot strike phase. The midsupport phase begins with full foot contact and lasts until the heel breaks contact with the support surface. During the midsupport phase, action at the hip and knee joints sequentially reverse from flexion to extension and action at the ankle joint shifts from dorsiflexion to

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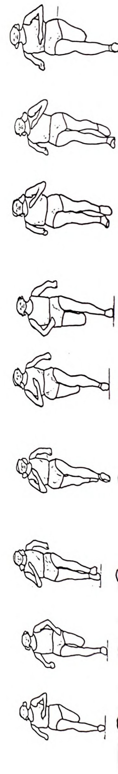
The recovery interval consists of the follow through phase, forward swing phase, and foot descent phase. The follow through phase begins the instant the toe leaves the support surface and continues until the thigh stops its backward movement. The forward swing phase begins with the forward movement of the thigh and ends when the thigh reaches its most anterior height position. Minimum knee angle occurs during this forward swing phase. The foot descent phase begins when the thigh reaches its maximum anterior height and ends with touchdown. Figure 13 summarizes the components of the running cycle.

Leg Action - Drive Interval. The functions of the leg in the drive interval of the running stride are to: (a) absorb the impact of foot strike, (b) bear the body weight, (c) arrest the downward motion imparted by gravity, (d) accelerate the body's center of gravity and (e) maintain forward motion along a given line of progression with minimal energy expenditure and loss of momentum (James & Brubaker, 1972, 1973; Hay, 1985). At slow to moderate speeds, foot touchdown usually occurs heel first; whereas at faster speeds the first contact may be with the ball of the foot. At the moment of touchdown, the foot is moving in a backward direction relative to the body's motion at a velocity



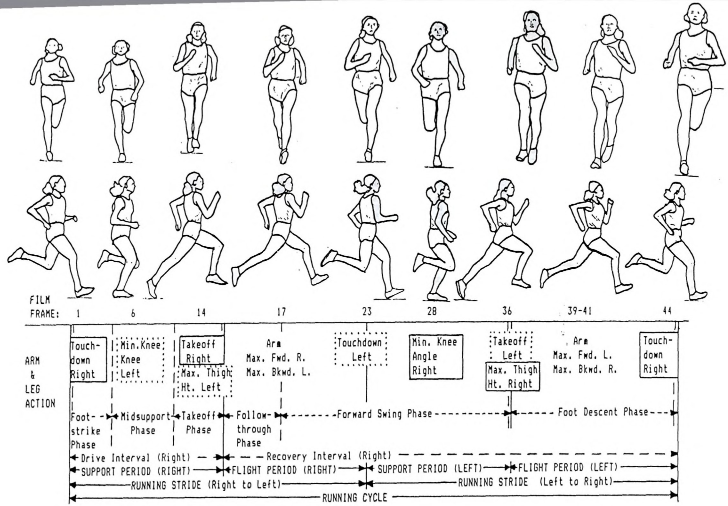


Figure 13. Summary of the components of a running cycle.

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approximately equal to the forward velocity of the body (Dyson, 1970; Fenn, 1930; James & Brubaker, 1972, 1973; Hay, 1985; D. Miller, 1978; Slocum & James, 1968). At contact, the lower leg creates an angle between 70° and 80° relative to the perpendicular. The foot touches down just slightly ahead of the downward vertical projection of the body's center of gravity. The faster and more mature the run, the shorter the distance between the downward vertical projection of the body's center of gravity and the point where the foot makes support surface contact, assuming a level surface (Dyson, 1973; Fenn, 1930; Hay, 1985). The short horizontal distance between the downward vertical projection of the body's center of gravity and place of foot touchdown and the backward direction the foot is moving at the instant of touchdown tend to reduce the braking action of contact. This helps maintain forward momentum since the foot is already moving in the direction of the drive at contact (Hay, 1985). Located on the ground, the center line of progression is an imaginary, single straight horizontal line traveling the same direction as the runner and falls within the midsagittal plane. The midsagittal plane of the body is that imaginary vertical plane that bisects the body into equal right and left halves. Each foot should strike the supporting surface parallel to and on its respective side of the midsagittal plane. Too great a variation from the center line of progression in the placement of the support foot will affect lateral balance and create a weaving action relative to the center line of progression (Dyson, 1973; Slocum & James, 1968; Wilt, 1964).

The human body, in a nonsupported state, behaves as a projectile and is governed by th

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and is governed by the laws of physics pertaining to projectiles (Hay, 1985). The magnitude of the parabolic flight path is determined by the speed, height and angle of takeoff, any air resistance, and the downward force of gravity. At touchdown, to help absorb the downward force of gravity and the body weight on the support surface as the foot makes first contact, flexion occurs at the hip and knee and dorsiflexion occurs at the ankle joint. The knee is already flexed 30° to 35° at touchdown (James & Brubaker, 1972) and flexes another 10° (Fenn, 1930) as the foot settles into the midsupport phase of the drive interval. Slight flexion is maintained at the hip, knee, and ankle joints as the body moves forward over the foot. Then, extension begins at the hip and knee joint and plantar flexion occurs at the ankle joint helping to drive the body up and forward into the takeoff. The summation of forces that launch the body into the air begins in the lumbar spine-pelvic musculature and progresses sequentially into the extensors of the hip, extensors of the knee, and plantar flexors of the ankle (Dyson, 1973; James & Brubaker, 1972; Slocum & James, 1968). In most instances, the leg reaches its maximum extension as the foot leaves the ground at takeoff.

Leg Action - Recovery Interval. The leg action during the three phases of the recovery interval involves reversing the direction of motion of the leg during each phase and, therefore, takes much more time than leg action in the drive interval (James & Brubaker, 1972, 1973). When the leg enters the first phase, the follow through phase, there is a momentary continuation of backward movement of the thigh segment.

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Flexion at the knee begins as the recovery limb decelerates and the flexor muscles of the hip are stretched to a length most suitable for subsequent contraction. That is, at takeoff the lumbar spine reaches its maximum extension, the upper pelvis tilts to its most forward position, the body reaches its maximum rotation about the vertical axis, the hip and knee move to maximum extension, the ankle reaches its greatest plantar flexion, and the foot reaches to its farthest position behind the body axis (Slocum & James, 1968). This continued backward movement of the lower leg and foot serves two purposes. First, it provides a controlling factor so that the follow through occurs with optimum timing. Entering the follow through too soon would exert a braking action and would require strenuous muscular effort (Slocum & James, 1968). Second, the continued backward motion of the lower leg and foot about the knee shortens the limb, thereby enabling the forward swing to occur with greater speed and less effort than if the leg were not flexed (Hay, 1985; James & Brubaker, 1972, 1973; Slocum & James, 1968; Wilt, 1964). As angular momentum is being transferred from the rearward swinging thigh segment to the lower leg and foot, the lower leg and foot continue their backward movement until the foot is near the buttocks. The flexion that begins in the lumbar spine during the follow through phase, progresses to backward upper pelvic tilt, hip flexion, and knee flexion.

The initial forward movement of the thigh segment marks the beginning of the forward swing phase. During the forward swing phase the thigh segment reaches its maximum height, relative to the horizontal, at the same moment that the opposite leg is completing its takeoff phase. The v

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takeoff phase. The vigorous upward and forward drive of the thigh, combined with the downward and backward movement of the drive leg, increases the support surface reaction forces, thereby increasing speed (Dyson, 1973; James & Brubaker, 1972, 1973). The foot descent phase begins after the thigh segment has reached its maximum height and the body is in flight. The thigh segment begins to move downward and backward, transferring angular momentum to the lower leg as it swings forward. Hamstring contraction decelerates the lower leg as the foot reaches its most forward position (Brandell, 1973). The knee maintains approximately 35° of flexion as the total leg completes a change in direction of travel from forward to backward in preparation for touchdown (James & Brubaker, 1972, 1973).

Arm Action. The downward and backward driving of the support leg in the takeoff phase sets up a line of reaction from the support surface up through the support leg that creates a rotation of the pelvis about the vertical axis of the trunk. This rotation of the pelvis continues in one direction until the opposite leg pushes against the ground, then the rotation reverses direction. For efficient running to occur, this pelvic rotation must be counter balanced through effective, compensatory and synchronous arm swing (Hay, 1985; Housden, 1964). At slow running speeds shoulder rotation also is effective in absorbing the rotational forces of the legs. However, shoulder rotation requires time, and therefore is an inefficient method of force absorption for sprint running. In sprint running, it is important to keep the shoulders steady and use forceful arm action to absorb the rotational force of the pelvis (Hay, 1985; Hi

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The upper arms move more or less straight forward and backward, whereas, the lower arms will have a slight cross-body direction in front. This slight cross-body swing of the lower arms is due to the natural hang of the upper limbs which results in a forward arm swing that is slightly diagonal rather than directly forward. The extent of the cross-body swing of the lower arms varies somewhat with individual body build and running speed (Broer & Zernicke, 1979). The hands should not cross the midline of the body. The faster the run, the less cross-body movement should be made by the arms. Hands should swing no more than shoulder high in front nor more than a foot behind the hip line. Elbows may be flexed as much as 90° at the apex of the front swing and should relax slightly as they move past the hip line (Dyson, 1973; Hay, 1985; Wickstrom, 1983; Wilt, 1964). The extent of elbow flexion is controlled by the same principle that governs knee flexion during the forward swing phase of the recovery interval. The principle s that as limb movement increases, shortening the radius of the limb by lexing the limb joints reduces the moment of inertia which in turn educes the resistance to angular movement and therefore enables the imb to move faster than if it were extended, given the same amount of pplied force (Hay, 1985; Simonian, 1981).

For arm swing to be an effective aid in force production as well as n the absorption of counter rotary forces, motion must be in the irection that will contribute positively to the running speed. It is portant when running fast that the arm movement not only be in a rward and backward line of direction, but also have significant upward and downward accelera

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ınd downward acceleration. Working synchronously in opposition, as the :wo arms complete the forward and backward swinging motion on each side ıf the body, they also move downward and upward. Properly synchronized ith the legs, the upward movement of each arm adds to the vertical omponent of the support leg drive at takeoff (Dyson, 1970; Hopper, 964).

Body Position and Displacement. The body position assumed while unning is adapted to the purpose for which one is running. However, nless one needs to make specific adjustments in the running situation, ıe runner generally maintains an upright trunk position and tracks the eet under the body parallel to a line of intended travel. Efficient ınning form gives the illusion of forward lean as the foot pushes off om the support surface, but the trunk essentially maintains the near ıright position. Maintaining a near upright trunk position is ıportant in achieving optimum flexion and extension of the legs during stride.

In smooth, efficient running there is minimal lateral body splacement in the frontal plane and minimal vertical displacement in e sagittal plane. These lateral and vertical displacements are aluated by the following changes in the body's center of gravity ring a running cycle. In the frontal plane, some side to side vement of the center of gravity is expected as the body weight is ternately transferred from one foot to the other. However, these teral movements should be kept at a minimum in order to reduce the rk of the postural muscles in maintaining body balance, to reduce the stress on the

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tress on the ankles, knees, and hips, and to avoid a weaving motion. ikewise, vertical displacement in the sagittal plane should be kept to minimum. Maximum forward displacement of the total body is desirable ince the greater the forward displacement in the sagittal plane, the reater the potential speed, other things being equal (Slocum & James, 968).

Researchers are in agreement that the path of the body's center of avity follows a wavelike pattern in the sagittal plane. The whole dy synchronously rises reaching its maximum height just after the keoff phase. A rise in the center of gravity within the body takes ace while the runner is in contact with the ground. Once in the air e body, the same as any projectile, follows a parabolic path rising d falling toward the ground (Hay, 1985). The action of the arms and gs causes shifting of the center of gravity within the body itself. fact, according to Fenn (1930), the synchronous changing limb sitions causes the body's center of gravity to move within the body, rst diagonally upward and backward, then downward and forward, twice ring each running cycle. Due to the influence of arm and leg vements, there is actually greater vertical range in the body's center gravity within the body than the relative up and down movement of the nner's head (Housden, 1964). The range of the vertical (up and down) vement of the body's center of gravity is inversely related to running eed. That is, the faster the running speed the less rise and fall of body's center of gravity for any given performance (Fenn, 1930; hanen & Komi, 1978; R.A. Mann & Hagy, 1980; Rapp, 1963).

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Effects of Speed (Velocity) Changes. Running speed (velocity) is the product of stride length and stride rate. Stride length is the distance covered from touchdown on one foot to touchdown of the opposite foot and stride rate is the number of strides taken within a given time period by the runner. A runner's stride length is the sum of three separate distances:

1. The takeoff distance is the horizontal distance that the downward vertical projection of the center of gravity is in front of the takeoff foot at the instant the foot leaves the support surface,
2. The flight distance is the horizontal distance that the body's center of gravity travels while the runner is in the air, and
3. The landing distance is the horizontal distance that the portion of the foot which first contacts the support surface of the touchdown foot is forward of the downward vertical projection of the body's center of gravity (Hay, 1985).

tride length and stride rate are interdependent and must be in correct roportion to achieve maximum running efficiency (Dyson, 1970; Hay 985). Within human physical limitations, increases in running speed re achieved by increasing both stride length and stride rate or by ntensifying one parameter without decreasing the other. As speed in- reases several related factors change:

. The time it takes to complete one stride decreases.
. More time is spent in flight and less time in support.
. Greater extension of the support leg occurs at takeoff.

The recovery leg achieves a smaller knee angle, moves faster, and

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the thigh segment moves higher relative to the horizontal before beginning descent to touchdown.

. The vertical displacement of the body's center of gravity decreases.

. The angular velocities at the leg joints increase.

. The angular displacements of the segments about the hip and knee increase while the angular displacements of the segments about the ankle decrease. The angular displacement of the trunk also decreases.

ble 3 summarizes the research that describes changes in the running ctors as speed increased.

Characteristics of Mature Running Form. In compiling reviews of nning research, Dillman (1975), Wickstrom (1983), and Williams (1985) scussed the difficulties encountered in attempting to interpret data running skill from the variety of protocols used to investigate the chanics of running. Williams (1985) identifies 10 variables which may ve varying influence on results: speed, sample size, gender, age, atomical and muscular characteristics, ability or state of training, erimental conditions and procedures of analysis, fatigue, handicap/ hology, and footwear/surfaces. Dillman (1975) particularly noted t when comparing the research on the effects of speed one should note ther the subjects were accelerating (continually increasing the rage horizontal speed) or moving at a constant (average horizontal) ed throughout the running cycles. Researchers often reported how jects ran at various constant speeds, within a certain range, which e 'discretely' incremented, without indicating if the same mechanical

Table 3

Summary of Running Factors that Change with Increases in Speed (Velocity).

Factor	Increase (+)/ Decrease (-)	Reference
Stride Length	+	Dillman, 1975; Fenn, 1930; Hanson, 1975; Hogberg, 1952; Kurakin, 1972; Luhtanen & Komi, 1978; D. Miller, 1978; Nelson & Gregor, 1976; Rapp, 1963; Saito, Kobyashi, Miyashita, & Hoshikawa, 1974; Slocum & James, 1968; Wickstrom, 1983; Williams, 1985.
Stride Rate	+	Dillman, 1975; Hogberg, 1952; Kurakin, 1972; Luthanen & Komi, 1978; D. Miller, 1978; Nelson & Gregor, 1976; Saito, et al. 1974; Slocum & James, 1968; Wickstrom, 1983; Williams, 1985.
Stride Time	-	Dillman, 1975; Hoskikawa, 1973; Kurakin, 1972; Wickstrom, 1983.
Thigh Segment Height	+	Dillman, 1975; Fenn, 1930; Hanson, 1975; Hoskikawa, 1973; D. Miller, 1978; Wickstrom, 1983; Williams, 1985.
Minimum Knee Angle	-	Dillman, 1975; Hanson, 1975; D. Miller, 1978; Wickstrom, 1983; Williams, 1985.
Speed of Leg Recovery	+	Hanson, 1975; Hoskikawa, 1973.
Support Time	-	Dillman, 1975; Hanson, 1975; Hoskikawa, 1973; Kurakin, 1972; Luhtanen & Komi, 1978; D. Miller, 1978; Nelson & Gregor, 1976; Slocum & James, 1978; Wickstrom, 1983; Williams, 1985.
Flight Time (> Support Time)	+	Dillman, 1975; Hanson, 1975; Hogberg, 1952; Kurakin, 1972; Luhtanen & Komi, 1978; D. Miller, 1978; Wickstrom, 1983; Williams, 1985.
Greater Leg Extension at Takeoff	+	Dillman, 1975; Hogberg, 1952; D. Miller, 1978; Wickstrom, 1983.
Vertical Displacement	-	Dillman, 1975; Fenn, 1930; Luhtanen & Komi, 1978; R.A. Mann & Hagy, 1980; Rapp, 1963; Wickstrom, 1983.
Angular Velocities	+	Hoskikawa, 1973; D. Miller, 1978.
Angular Displacement		
Hip	+	Hoskikawa, 1973; Wickstrom, 1983.
Knee	+	Hoskikawa, 1973; Wickstrom, 1983.
Ankle	=	Hoskikawa, 1973.
Trunk	-	Hoskikawa, 1973.

changes were evident if a runner was continuously and rapidly accelerating through the same range of speeds. Dillman (1975) and Wickstrom (1983) advised that a reviewer should note whether overground or treadmill running was used in a study. Conflicting results were obtained in the research that was specifically designed to compare overground and treadmill running (Dal Monte, Fucci, & Manoni, 1973; Elliott & Blanksby, 1976; Nelson, Dillman, Lagasse, & Bickett, 1972). Elliott and Blanksby (1976) equated jogging and running overground with treadmill jogging and running in males and females. No differences were noted among the subjects in stride length, stride rate, support and flight times at jogging speeds, but at running speeds stride length decreased, stride rate increased and flight time was less when running on the treadmill in contrast to running on the ground. Nelson et al. (1972) found the support period increased while vertical velocity decreased and that vertical and horizontal velocities were less variable on the treadmill than on overground running. Nelson et al. (1972) concluded significant mechanical changes did occur when running on the treadmill as compared to overground running. On the other hand, Dal Monte et al. (1973) concluded running technique was no worse on the treadmill than overground because there were no significant kinematic differences evident within the two running forms. The type of subjects used (good vs poor, elite runner vs recreational jogger) and the subjects' familiarity with treadmill running also may have affected the results and must be considered when contrasting results of research on mature running form.

Despite the inconsistencies and differences among the subjects and ocols used, certain characteristics of mature running form are ent throughout the literature. Dillman (1975) and Wickstrom (1983) summarized the characteristics of mature running form. These two ors conclude that relative to the immature runner, the mature er:

Has a longer length of stride relative to the physical dimensions of the body.

Spends less time in contact with the ground.

Has a smaller vertical displacement of the body.

Has greater angular velocities and complete extension of the leg during the takeoff phase of the drive interval.

Has greater knee flexion during the forward swing phase of the recovery interval.

Has a more efficient sequential backward rotation (with respect to the trunk) of the leg just prior to touchdown during the foot descent phase of the recovery interval.

Has less knee flexion and ankle dorsiflexion in the support leg after the foot makes contact with the ground.

Has thigh segment reaching a greater height relative to horizontal during the recovery interval.

Has touchdown of the foot closer to the downward vertical projection of the body's center of gravity.

Maintains only a very slight forward lean of the trunk throughout the running cycle.

Swings the arms forward and backward in synchronized opposition to the leg action allowing the hands to move toward the body's midline on the forward swing.

mary

This review of literature has reflected the interdisciplinary proach of the present study by recapitulating the biological and ychological origins of developmental stage theory; the Piagetian iteria for stages (hierarchization, structural wholeness, integration, nsolidation, and equilibration) and their application to motor skill velopment; the major early research in motor skill development; the velopmental staging research for fundamental motor skills; the velopment of running from both developmental staging and developmental omechanics research; and finally, the biomechanical analysis of the ture running form to serve as a basis for measuring skill development.

Physical educators have taken two approaches to the study of the velopment of running. Physical educators specializing in velopmental biomechanics have analyzed running in order to describe fferences and trends in skill performance on the basis of age or nder, kinematic, and kinetic variables. Physical educators ecializing in motor development have staged skill development cording to specific characteristics observed in skill development. dependently, motor development and developmental biomechanical proaches to motor skill maturation research have yielded valuable formation about the development of fundamental motor skills in ildren. Both approaches have provided quanititative and qualitative formation (direction and shape of developmental changes, mathematical

arameters of developmental curves, and distance, speed, and velocity
cores on skill performance) by age or grade and gender. Developmental
.omechanical studies have provided kinematic and kinetic information on
iat is happening to body segments and joints during skill performances
children of differing ages or grades and gender. Motor development
aging studies have identified age related, but not age dependent,
anges for key descriptive characteristics in developing fundamental
tor skills in boys and girls. The key descriptive characteristics
entified by motor development staging studies are generally synonymous
kinematic variables investigated by age or grade level in
velopmental biomechanics studies. However, biomechanical analysis of
e identified developmental stages of various fundamental motor skills
defined has yet to be done. For the motor development researcher, a
omechanical analysis of the developmental stages of fundamental motor
ills would help determine the extent and significance of mechanical
fferences observed in developing skills. For the developmental
omechanics researcher a biomechanical analysis of the developmental
ages might begin to explain differences, or lack of differences found
previous research based on age or grade level. The present study
gan the process of biomechanical analysis of the developmental stages
fundamental motor skills by investigating selected kinematic and
thropometric variables for the skill of running. Its purpose was to
fine which specific variables, if any, differ among the four stages of
nning as well as between the running performance of boys and girls.

Chapter III

Methodology

The purpose of this study was to identify differences in selected ıematic variables among the four developmental stages of running in ɜschool age boys and girls. This chapter will describe the subjects ɜd in the study, the protocols for the anthropometric measurements, ɔcedures for the filming session, data reduction, analysis of data, research design, and statistical treatment of the data.

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A pool of potential subjects for each developmental stage of ning was identified during the fall 1985 testing of all enrollees in Early Childhood Motor Development Program (E.C.P.) in the School of lth Education, Counseling Psychology, and Human Performance at higan State University. Each fall and spring, enrollees are tested stage of development in ten fundamental motor skills, distance in long jump, and performance times for balancing on each foot, an lity run, and a 15/30-yard run. The 15/30-yard run requires a ning start and times are taken at the 15-yard and 30-yard marks using ɔlit time stopwatch. During the fall 1985 sessions, the author was present at all testing sessions in order to identify enrollees exhibiting the classic stages of running as previously described. After a child was so identified, the accompanying parent was given a brief explanation of the study and asked for verbal permission to include that child in the appropriate subject pool. Since few program enrollees demonstrate a stage-one run, younger siblings of children being tested were screened, with parental permission, to create a subject pool for stage-one runners.

Because there was approximately a six-month interval between the fall testing and the actual filming, all children enrolled in the E.C.P. program during the spring term were rechecked for running stage approximately one month prior to the filming. This verification was conducted at one of the teaching stations during the weekly E.C.P. classes which the children attended. Running stages were determined and 15/30 yard run times were collected. The pool of potential subjects for each running stage was adjusted for children who had moved into transition since the September screening. Between this second screening and film data collection, the author visited the weekly classes in which the selected subjects were enrolled. These visitations helped establish a positive rapport with the children in preparation for the filming sessions. Visitation of E.C.P. classes during the week prior to filming provided opportunity for a final verification of the stages.

From the four subject pools, one boy and one girl (n=8) were selected who nearest represented the modal age for each stage (stage 1 = 18-23 months, stage 2 = 30-35 months, stage 3 = 42-47 months, stage 4 = 54-59 months) (Early Childhood, 1985). Parents were contacted by telephone to ascertain interest in bringing their children in for a filming session. If the response was positive, a filming time was tentatively scheduled and the parents were sent information detailing the study. Copies of the parent information materials are contained in Appendix B. If the parents had any questions or concerns after having read these materials, they were requested to contact the author.

Testing Procedures

All subjects were scheduled for a single filming session held at the Center for the Study of Human Performance in Erickson Hall on the campus of Michigan State University. Upon their arrival, informed consent forms and film release forms were collected from the parents, and the children were given a brief tour to familiarize themselves with the lab filming area and the film personnel. With the youngest children a brief play period with foam balls helped them become more comfortable with the film personnel. Testing procedures for each subject involved the collecting of anthropometric data and completion of two film trial runs. Specific explanations for each procedure follow.

Anthropometric Measurements. Prior to the actual filming, selected anthropometric measurements were taken on each subject for statistical analysis of the relationship of body segment lengths to running stage. Dressed only in a swim suit (or diapers), the subjects were weighed on a weight-beam scale. Weight was measured to the nearest one-tenth kilogram. The subjects then were shown the measuring tools, a bow

caliper and an anthropometer, and were told that these would be used to find out "how big you are." For each measurement the children were given a demonstration of how they should try to stand or sit. If they were unable to copy the position on their own they were gently placed into the correct position. Measurements to the nearest millimeter were taken on both sides of the body following procedures outlined by Seefeldt, Haubenstricker, Brown, and Branta (1983) and recorded. The selected anthropometric measurements were: standing height, sitting height, shoulder width (biacromial diameter), hip width (biiliac diameter), upper-arm length (acrom-radiale), forearm length (radio-stylion), hand length, total upper extremity length, foot length, shank length, total leg length, and trochanteric height. A detailed description of the measurements can be found in Appendix C.

Cinematographic Procedures. After the anthropometric measurements were recorded the investigator marked the body joints with 3/4 inch round, contrasting markers. The joint markers were applied to assist in achieving more precise and uniform location of body joints during data analysis (Ulibarri, 1984). The subjects ran from left to right as viewed through the field of view of the sagittal camera (side view). Joint markers were placed on the lateral side of the right ankle, knee, and hip, and on the medial side of the left ankle, and knee. Lateral, medial, and front sides of each elbow were marked as were the front, lateral, and back sides of each shoulder. Wrist joints were marked with specifically designed contrasting 3/4 inch elastic bands to insure easier identification of this joint from any position. The front of

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each hip, knee, and ankle also were marked. The children also received a special "belly-button" marker (Mersereau, 1974). They were told they couldtouch and take home this novelty marker, but the other markers were to be left untouched.

The running surface in the staging area of the lab was marked to coincide with the filming field of view and to create a running track so the children could be instructed to run between the lines. Cross lines were placed one meter apart down the length of the runway. Along with the filming of a meter stick prior to the actual filming of a subject, the cross lines provided a known distance reference on the film for use in data analysis. Figure 14 illustrates the track area and placement of the cameras. The children were shown the running track and given a practice run. Prior to the actual filming of the running, the children were given an opportunity to listen to the camera sounds while the meter stick was filmed. This meter stick was used as the linear conversion factor in the planar analysis. Once familiar with the sound, the subjects were much less distracted during the filming trials. The children were then filmed from the sagittal (side view) and frontal planes (front view) simultaneously while they ran down the marked track to one of their parents who was waiting beside the frontal plane (front view) camera. Orange cone markers were placed on the end of the running track nearest the frontal plane (front view) camera, just inside the field of view of the sagittal plane (side view) camera. The children were asked to run as fast as they could, straight between the cones, and give their parent a big hug. Except for the addition of the cone markers and the marked track, the directions were identical to the ones

Plum Line

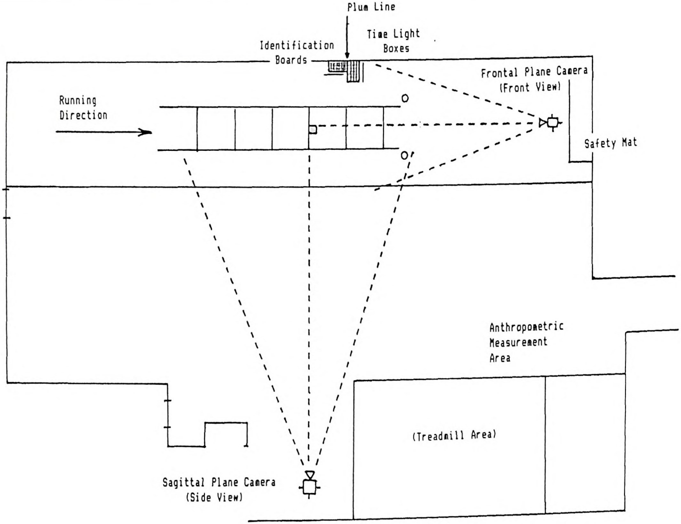

Figure 14. Floor plan of the filming area.

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used for the semiannual testing of the children enrolled in the Early Childhood Motor Skills Development Program. The cone markers and floor lines marking the running track were added to keep the children running in a straight line to minimize perspective error as each child moved through the field of view of the sagittal camera (side view). A minimum of two good trials was filmed. Additional trial(s) were filmed if the child failed to achieve a full run or broke stride before exiting the field of view of the sagittal camera (side view). The trial selected for analysis was the one that demonstrated the best performance or quality of film from the sagittal view (side view).

Two LOCAM cameras equipped with F .12-120mm zoom lenses were used in the filming. The cameras were mounted on separate tripods and each connected to a master switch with a 25 foot heavy duty extension cord. Kodak 4-X Reversal 7277 high speed 16mm film was used for the filming. The film rate was 100 frames per second with a 120° shutter angle and a 5.6 f-stop for the sagittal plane (side view) camera and a 4 f-stop for the frontal plane (front view) camera. This created a 1/300th second exposure time and eliminated blurring of the movement on the film. The lens on the frontal plane (front view) camera was set at 7m (lens length = .15m) and the lens on the sagittal plane (side view) camera was set at 20m (lens length = .16m). Timing light boxes capable of measuring up to 1/1000th second, plumb lines, and subject identification boards were placed each camera's field of view. The sagittal plane (side view) camera was placed on a tripod 1.06 meters high and 12.4 meters from and perpendicular to the running track. The frontal plane (front view) camera was on a tripod 1.12 meters high and was perpendicular to and cente

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centered between the two lines that marked the running track. The frontal plane (front view) camera was 6.27 meters from a point that represented the center of the field of view for the sagittal plane (side view) camera so that a right angle was formed where the central focal point from each camera met (see Figure 14). The staging area was lit by two banks of ceiling flood lights and a gray CBS curtain provided the backdrop. Skill eliciting was done by the researcher, while camera control was handled by an expert in cinematography. Four graduate assistants (two during the morning filming sessions and two in the afternoon filming sessions) provided general technical assistance.

Data Reduction and Analysis

The analysis first required data reduction of the film. This yielded the needed raw data to complete the kinematic and statistical analyses according to the research design.

Film Analysis. Data reduction was performed by the process of digitization. The film was projected onto a drafting table by a Van Guard Analyzer projection head. A sonic stylus was used in conjunction with two strip microphones set perpendicular to each other on the drafting table. Every frame for one running cycle for each leg was digitized. Seventeen data points were input for each frame as illustrated in Figure 15. Data were read directly to an IBM PC floppy disk then transferred to the Cyber 750 mainframe computer at the Michigan State University Computer Center for analysis using the

Figure 15
segments.
limbs.

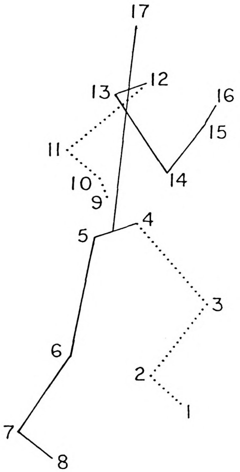

Figure 15. Numbering of the designated end points for digitizing body segments. Solid line indicates right limbs, dotted line indicates left limbs.

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biomechanics program, KINEMAT. This program supplied data for analysis of segmental and body centers of gravity, and linear and angular displacements, velocities, and accelerations. Raw data were smoothed using the First Central Taylor Expansion Series Equation. A conversion factor was calculated and used in the linear calculations. Frame time was verified by the timing lights. To determine lower extremity joint angles, segmental inclinations were measured relative to the horizontal as illustrated in Figure 16. Trunk inclination was measured from the midpoint of the hip joints relative to the horizontal as illustrated in Figure 17. Lower extremity segmental inclinations were evaluated at touchdown and takeoff during the drive interval (see Figure 18), and at minimum knee angle (see Figure 19) and maximum thigh segment height (see Figure 20) during the recovery interval. Upper extremities were measured in a similar manner. Segmental inclinations for the humerus and forearm were measured relative to the horizontal as illustrated in Figure 21. Humerus and forearm inclinations were evaluated at the maximum forward swing and at maximum backward swing as illustrated in Figure 21.

Displacements and velocities were investigated in two ways. First, the displacements and velocities for upper and lower limbs were tabled for comparisons among the four running stages. Second, the sequence of peak angular velocities in the lower extremities were determined for comparison among the four stages. All data were calculated from film of the sagittal (side) view.

Also measured from the sagittal film (side view) data was the horizontal distance between the lead foot at touchdown and downward

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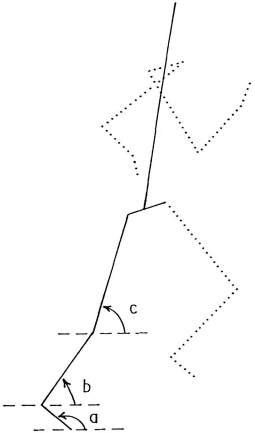

Figure 16. Segmental inclinations for analysis during the drive interval: (a) foot, (b) shank, (c) thigh.

Figure 17.

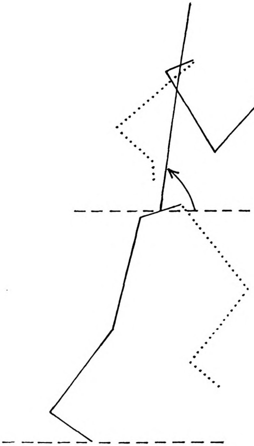

Figure 17. Measurement of trunk inclination.

Figure 18. S
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(b) takeoff.

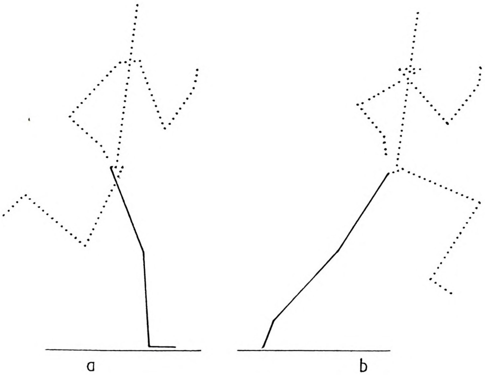

Figure 18. Selected positions for lower extremity segmental inclination measurements for analysis during the drive interval: (a) touchdown, (b) takeoff.

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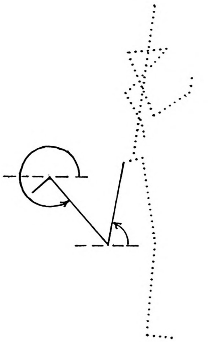

Figure 19. Measurement of segmental inclinations for analysis of minimum knee angle during the recovery interval.

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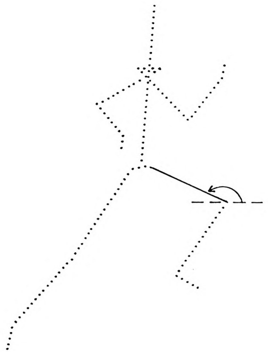

Figure 20. Measurement of segment inclination for analysis of maximum thigh segment height during the recovery interval.

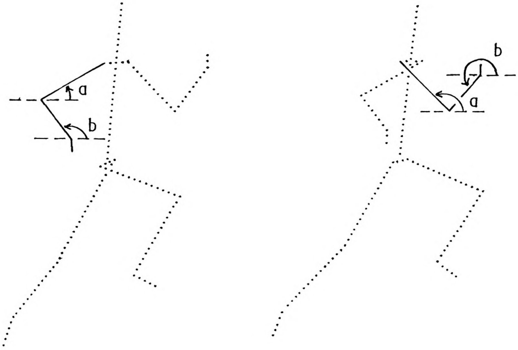

Figure 21. Measurement of upper extremity segment inclinations for analysis of (a) humerus and (b) forearm at maximum backward and forward swing.

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vertical projection of the body's center of gravity at touchdown (see Figure 22). This distance was measured for each foot at touchdown. Additionally, the stride length and stride rate were measured and running velocity was calculated from the sagittal view (side view) film.

From the frontal plane (front view) film the distance between a drawn midline and the segment center of gravity for the hands, forearms, humeri, thighs, shanks, feet, and the midpoint betwwn the two shoulder joints were evaluated at selected points during the one running cycle for each leg analyzed. During the drive intervals for each leg the measurements were taken at touchdown and takeoff. During the recovery intervals, the measurements were taken at minimum knee angle and maximum thigh segment height. Figure 23 illustrates the procedure for measurement of the distances between the drawn midline and the segmental centers of gravity for the hands, forearms, humeri, thighs, shanks, feet, and the midpoint between the two shoulder joints.

Research Design. This investigation was designed to study selected kinematic variables (positions in space and linear and angular displacements and velocities) and anthropometric measurements in relation to the four developmental stages of running in preschool age boys and girls. Data were collected during a single measurement and filming session. Running stage and gender were the independent variables, while the selected kinematic variables and anthropometric measures were the dependent variables. This created a 4 x 2 design with multiple dependent variables. Film data were obtained for at least two good trials. The best trial was selected for analysis.

Figure 22. Meas
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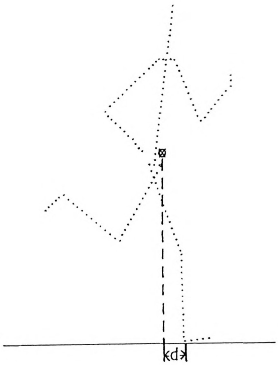

Figure 22. Measurement of the horizontal distance between the downward vertical projection of the body's center of gravity and the foot at touchdown.

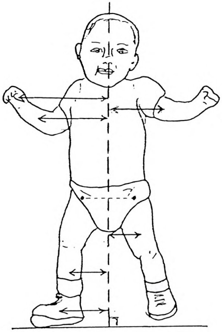

Figure 23. Measurements for the relationship of segment center of gravity of the hands, forearms, humeri, thighs, shanks, and feet with the drawn midline (center line of progression).

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<u>Statistical Analysis</u>. Data were analyzed on the University of Missouri system IBM 3278 mainframe computer at the University of Missouri-St. Louis Computer Center using the SAS Version 5 (1985a, 1985b) statistical programs. A p value equal to or less than .05 was considered significant.

Data were analyzed at specific points during one complete running cycle for each leg using multivariate analysis to determine the overall significance of the differences in performance among the four stages of running. Univariate F, planned comparison tests and, where indicated, post hoc tests then were used to define which specific kinematic, anthropometric, or both variables differed between the four stages. Correlations were performed to determine the relationships between stride length and stride rate, stride length and running velocity, stride rate and running velocity, and trochanteric height and running velocity.

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Chapter IV

Discussion of Results

An interdisciplinary approach was used in this study of running development in young children. Biomechanics research techniques, specifically selected kinematic-analysis procedures using high speed cinematography, were used to evaluate the differences among the four developmental stages of running (Seefeldt et al., 1972) and between gender groups. Kinematic variables selected for investigation represented the distinguishing characteristics of the developmental stages of running. Seven major areas were investigated and will be discussed in the following pages. These areas of investigation included: (a) the running descriptors of stride length, stride rate, stride time, cycle length, total right-left cycle distance, total right-left cycle time, running speed, and selected anthropometric measures; (b) the segmental inclinations at selected points during the running cycle; (c) the distance between the downward vertical projection of the body center of gravity and the foot at touchdown; (d) the sequence of peak angular velocity for leg segments; (e) the midline-limb segment center of gravity distance at selected points during the running cycle; (f) the temporal analysis; and (g) limb segment displacements, both linear and angular. The variables were analyzed for each leg in order to ol

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to observe differences between right and left limb actions. Tabled raw data for the subjects studied can be found in Appendix E.

Running Descriptors.

Selected anthropometric measurements were analyzed for stage effect. Although trochanteric height was the leg measurement of choice for study, total leg length was also analyzed to compare with results from previous research on development of running in young children. Stage effect p values ranged from .0346 to .4372 and gender effect p values ranged from .0949 to .0662 for standing height, trochanteric height, total leg length, biacromial width, and biiliac width. Trochanteric height was statistically the same among the stage one, two, and three runners and the stage two, three, and four runners. The trochanteric height of stage one and four runners differed significantly at the $p < .05$ level (see Tables 4 and 5). There was no statistical difference for gender on trochanteric height. It is difficult to discern why the stage-effect significance occurred in trochanteric height and not in total leg length, unless the small number of subjects (and/or the .05 significant level used) in the study affected these factors. Perhaps analysis of both measures in future research should be performed to ascertain if the difference really is significant or is due to some other variable(s).

Mean stride time, stride length, stride rate, cycle length, total right-left cycle distance and total right-left cycle time were evaluated (see Tables 6 and 7). P values obtained for stage and gender effect

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Table 4

Analysis for Stage Effect on Selected Anthropometric Measures (cm).

	STAGE 1	STAGE 2	STAGE 3	STAGE 4	F (3,3)	p
STANDING HEIGHT	80.600	93.500	97.600	106.950	5.77	.0920
TROCHANTERIC HEIGHT	33.400	44.350	44.350	48.900	12.60	.0346
TOTAL LEG LENGTH (femur + shank)	30.550	40.400	41.150	45.050	9.51	.0484
BIACROMAL WIDTH	19.600	21.650	22.800	25.100	1.98	.2950
BIILIAC WIDTH	14.800	16.500	17.000	17.300	1.22	.4372

Table 5

Analysis for Gender Effect on Selected Anthropometric Measures (cm).

	GENDER MALES	GENDER FEMALES	F (1,3)	p
STANDING HEIGHT	90.175	93.150	0.44	.5539
TROCHANTERIC HEIGHT	42.300	43.200	0.23	.6660
TOTAL LEG LENGTH (femur + shank)	36.875	41.700	5.81	.0949
BIACROMAL WIDTH	22.325	22.250	0.00	.9662
BIILIAC WIDTH	16.525	16.275	0.06	.8207

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Table 6

Analysis for Stage Effect on Selected Running Measurements.

	STAGE 1	2	3	4	F (3,3)	p
MEAN STRIDE TIME (s)	0.240	0.232	0.227	0.212	0.450	.7371
MEAN STRIDE LENGTH (cm)	41.080	50.790	66.470	85.700	6.370	.0813
MEAN STRIDE RATE (#/s)	4.210	4.340	4.420	4.720	0.400	.7650
MEAN CYCLE LENGTH (cm)	78.430	100.240	130.300	170.300	6.300	.0842
TOTAL RIGHT-LEFT CYCLE DISTANCE (cm)	117.880	154.070	197.760	252.600	6.250	.0833
TOTAL RIGHT-LEFT CYCLE TIME (s)	0.710	0.700	0.685	0.630	0.650	.6337

Table 7

Analysis for Gender Effect on Selected Running Measurements.

	GENDER MALE	FEMALE	F (1,3)	p
MEAN STRIDE TIME (s)	0.241	0.215	2.280	.2278
MEAN STRIDE LENGTH (cm)	64.493	57.522	0.810	.4334
MEAN STRIDE RATE (#/s)	4.192	4.652	1.800	.2721
MEAN CYCLE LENGTH (cm)	127.090	112.540	0.840	.4264
TOTAL RIGHT-LEFT CYCLE DISTANCE (cm)	189.810	171.350	0.630	.4849
TOTAL RIGHT-LEFT CYCLE TIME (s)	0.715	0.647	2.330	.3344

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anged from .0813 to .7650. However, a clear developmental trend across tages can be observed for all variables. Males had longer stride ength, cycle length, total right-left cycle distance, stride time, otal right-left cycle time, and lower stride rate than females. These rends are in agreement with previously reported research (Amano et al., 983; Beck, 1966; Brown, 1978; Clouse, 1959; Dittmer, 1962; Fortney, 980; Glassow et al., 1965; Mersereau, 1974, 1977; Miyamaru, 1976; and nith, 1977).

Running cycle length, stride length, stride rate, and stride time ere also analyzed for within subjects right-left differences factor. P alues ranged from .1031 to .5287 for stage effect and .0367 to .7708 or gender effect (see Tables 8 and 9). Follow up test for $p<.05$ were on significant. The right running cycle was slightly longer (2.16 to 51 cm) than the left across all stages. Right stride length was nger (2.07 to 7.71 cm) in stages one, two, and three; left stride ngth was longer (3.60 cm) in stage four. As expected, this same ttern was seen in stride time. The opposite pattern is observed in ride rate. A faster (.25 to .77 #/s) stride rate on the left occurred stages one, two, and three, and on the right in stage four (.60 #/s). e males had longer running cycles (14.56 cm), stride lengths (6.97), stride times (.027 s), and slower stride rates (.49 #/s) than the males.

During the subject selection from among the children enrolled in e Early Childhood Motor Development Program (E.C.P.) in the School of alth Education, Counseling Psychology, and Human Performance at chigan State University, the children were timed as well as classified

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Table 8

Analysis for Stage Effect on Selected Right and Left Leg Running Measurements.

	STAGE 1	2	3	4	F (6,2)	p
RUNNING CYCLE (cm)					1.337	.4871
RIGHT	81.680	101.490	132.930	171.380		
LEFT	75.170	98.990	127.670	169.220		
STRIDE LENGTH (cm)					1.170	.5287
RIGHT	42.700	54.670	70.000	83.900		
LEFT	39.450	46.960	67.930	87.500		
STRIDE RATE (#/s)					5.413	.1641
RIGHT	4.100	4.010	4.175	5.050		
LEFT	4.350	4.780	4.815	4.445		
STRIDE TIME (s)					9.022	.1031
RIGHT	0.245	0.250	0.240	0.200		
LEFT	0.235	0.215	0.215	0.225		

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Table 9

Analysis for Gender Effect on Selected Right and Left Leg Running Measurements.

	GENDER		F (2,2)	p
	MALE	FEMALE		
RUNNING CYCLE (cm)			0.297	.7708
RIGHT	128.940	114.800		
LEFT	125.250	110.280		
STRIDE LENGTH (cm)			0.678	.5958
RIGHT	64.559	61.050		
LEFT	64.427	53.993		
STRIDE RATE (#/s)			21.286	.0449
RIGHT	4.315	4.352		
LEFT	4.102	5.042		
STRIDE TIME (s)			26.274	.0367
RIGHT	0.238	0.230		
LEFT	0.245	0.200		

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nto stages for running performance. The running velocities for the ubjects selected for filming were then calculated and analyzed along ith the running velocities obtained from the film to see if there might e any notable changes over the approximate 30 day period between ubject selection (April, 1986) and actual filming (May, 1986). Stage ne velocities were only available from the film since these two ubjects were too young for the E.C.P. program. Analysis of velocity easures yielded a significanct effect for stage (see Table 10). The unning velocities obtained in April showed stage four runners were ignificantly (p.0117) faster than stage two and stage three runners. he running velocities recorded in May were slightly faster (.06 to 69 s) than those in April, especially among the stage three runners. ay running velocities were statistically the same for stages two, hree, and four, and for stages one, two, and three. Stage one and four iffered significantly (p .0392). Considering the two different onditions under which the velocities for stage two, three, and four unners were obtained, it was encouraging that the velocities and ignificance levels were similar. Unfamiliar situations can sometimes ave an adverse effect on skill performance in the preschool child. om the two sets of running velocity data it appeared that this rticular variable was not greatly affected by the unfamiliar mosphere of a human performance laboratory rather than the familiar C.P. gymnasium.

The velocities obtained from the film are in agreement with the rly Childhood (1985) study and several other studies involving eschool age children (see Table 11). In addition, Fortney's (1980)

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nalysis of Running Velocity (m/s) from Subject Selection Testing
April) and from Film (May).

	STAGE 1	STAGE 2	STAGE 3	STAGE 4		
SUBJECT SELECTION TESTING	not available	2.138	2.169	3.917	$F_{(2,2)} = 84.70$	$p = .0117$
FILM	1.696	2.196	2.859	4.017	$F_{(3,3)} = 11.13$	$p = .0392$

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Table 11

Comparison of Running Speeds (m/s) by Developmental Stage and Age from Selected Research ((n) = Number of Subjects).

STUDY AND SUBJECT CATEGORIZATION

DEVELOPMENTAL STAGES	1	2	3	4
Early Childhood (1985)	1.990 (11)	2.714 (308)	3.103 (576)	3.405 (287)
Kiger (1987)	1.696 (2)	2.196 (2)	2.859 (2)	4.017 (2)
AGE IN YEARS		2	4	6
Fortney (1980)		2.133 (6)	3.750 (12)	4.263 (10)
Mersereau (1974)		1.938 (4)		
Miyamaru (1976)		2.470 (6)	3.665 (20)	4.270 (10)
			3	5
			2.945 (18)	4.105 (15)

running indices for her 2-, 4-, and 6-year old subjects provided some interesting comparisons to the four developmental stages of runners in the present study. In the three indices compared in Table 12 (speed/leg length, speed/stature, and mean step length) Fortney's (1980) 2-year olds differed significantly from her 4- and 6-year olds. Although the two studies cannot be directly compared (age level versus developmental stage level), it is noteworthy that the indices for the 2-year olds are almost identical to those calculated for the stage two runners from the present study, and the indices for the 4-and 6-year olds are almost identical to those of the stage four runners of the present study. One question emerges. How much of the significance in previous age level studies might have been due to the skill pattern used in relation to the age of the performer?

The degree of relationship among a selected number of variables was of interest to this researcher. Several of the running descriptors were correlated to observe their relationship among the running stages. These correlations are presented in Table 13. In light of the significance found in trochanteric height and not total leg length, correlations were run for both variables and stride length, stride rate, and running velocity. The highest correlations were obtained for mean stride length versus running velocity (.97) and trochanteric height versus running velocity (.83). Trochanteric height correlated higher than total leg length with stride length and running speed, whereas total leg length correlated higher than trochanteric height with stride rate. Again it is difficult to discern why the higher correlations appeared for trochanteric height versus total leg length or vice versa,

Table 12

Running Indices by Age (Fortney, 1980) Compared to Running Indices by Stage (Kiger, 1987).

AGE - STAGE

(Number of subjects tested in each category)

Speed/Leg Length (m/s/m)					
	Age in Years		2	4	6
			5.981 (6)	8.326 (12)	8.330 (10)
	Stage	1	2	3	4
		5.725 (2)	5.505 (2)	7.051 (2)	8.963 (2)
Speed/Stature (m/s/m)					
	Age in Years		2	4	6
			2.373 (6)	3.479 (12)	3.572 (10)
	Stage	1	2	3	4
		2.088 (2)	2.477 (2)	2.920 (2)	3.761 (2)
Mean Step Length (m)					
	Age in Years		2	4	6
			.563 (6)	.940 (12)	1.167 (10)
	Stage	1	2	3	4
		.410 (2)	.508 (2)	.664 (2)	.857 (2)

le 13

relations for Selected Running Descriptors.

CORRELATED MEASUREMENTS	R
Mean Stride Length (cm) vs Mean Stride Rate (#/s)	0.2427
Mean Stride Length (cm) vs Running Velocity (m/s)	0.9698
Stride Rate (#/s) vs Running Velocity (m/s)	0.4583
Trochanteric Height (cm) vs Stride Length (cm)	0.7815
Total Leg Length (cm) vs Stride Length (cm)	0.6007
Trochanteric Height (cm) vs Running Velocity (m/s)	0.8263
Total Leg Length (cm) vs Running Velocity (m/s)	0.7275
Trochanteric Height (cm) vs Stride Rate (#/s)	0.5284
Total Leg Length (cm) vs Stride Rate (#/s)	0.7548

ess the small number of subjects in the study affected these factors. ese correlation results reinforce the need to include both measures in ure research to ascertain the value of the current findings.

mental Inclinations

Segmental inclinations for the legs were investigated at four nts during one running cycle for each leg: touchdown of the foot to chdown of the same foot. During the drive interval, measurements e initially evaluated at touchdown and takeoff with maximum leg ension added when the data indicated this particular event occurred ore takeoff in most of the subjects. Trunk inclination was also luated at touchdown and takeoff. During the recovery interval surements were evaluated at minimum knee angle and maximum thigh ment height. Arm segment inclinations were evaluated at humerus imum forward swing and maximum backward swing positions. elopmental trend predictions were based on tracings made from earch films by Seefeldt et al. (1972) and Seefeldt and Haubenstricker 32). See Figures 1 through 6 (pp. 17, 19-21, 23-24). All linations were measured from the distal end of the segment, relative the horizontal.

Leg Drive Interval - Touchdown. During the drive interval elopmental trends for the leg segment inclinations at touchdown were dicted based on Figure 1 (p. 17). The greater the magnitude of the h and shank segment inclinations the more forward (relative to the

ownward vertical projection of the body's center of gravity) was the osition of the leg at touchdown. The greater the magnitude of the foot egment inclination the more the foot was dorsiflexed relative to the upporting surface. For the thigh segment at touchdown it was predicted hat the inclination would decrease from stage one to stage two, ncrease from stage two to stage three, and decrease from stage three to tage four. Data analysis of the subjects depicted in Figure 24 showed hat from stage one to stage two the left thigh followed the prediction nd the right thigh did not follow the prediction. From stage two to tage three both thighs decreased as opposed to the predicted increase n inclination. From stage three to stage four both thighs increased as pposed to the predicted decrease in inclination. For the shank at ouchdown it was predicted that the inclination would increase from tage one to stage two, then progressively decrease at stages three and our. The data indicated the left shank progressively increased from tage one to stage three then decreased from stage three to stage four. he right shank inclination decreased from stage one to stage two, ncreased from stage two to stage three and then decreased from stage hree to stage four.

The foot segment at touchdown was predicted to follow the same rends as the shank; increased inclination from stage one to stage two, hen progressive decreased at stages three and four. The data showed nat both feet did increase in inclination from stage one to stage two. rom stage two to stage three the right foot continued to increase while ne left foot decreased in inclination. From stage three to stage four ne right foot decreased in inclination whereas the left foot increased

FEMALE

MALE -

FEMALE

MALE -

Figure

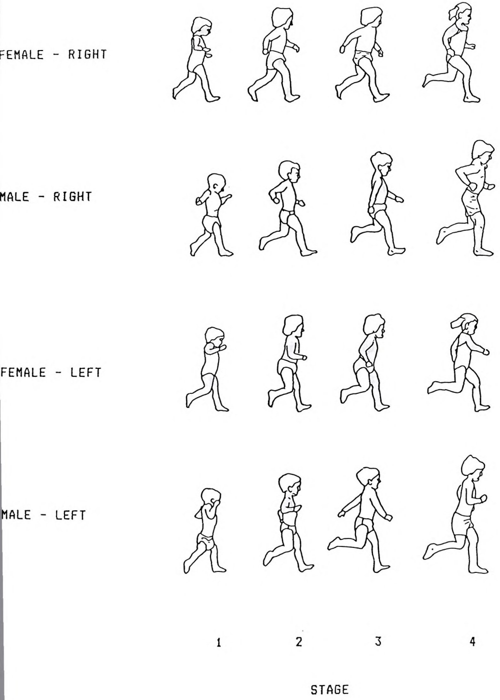

Figure 24. Film tracings of subjects at right and left touchdown.

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in inclination.

The right-left differences for each segment were interesting. The left thigh inclinations were greater (2.82°) than the right thigh inclinations at stage one and the right thigh inclinations were greater (5.06° to 10.19°) than the left thigh inclinations at stages two (10.19°), three (8.51°), and four (5.06°). The right shank inclinations were greater (6.13°) than the left shank inclinations at stage one and the left shank inclinations were greater than the right shank inclinations at stages two (1.75°), three (0.34°), and four (7.79°). Right foot inclinations were greater than left foot inclinations at stages one (11.48°) and three (14.13°). Left foot inclinations were greater than right foot inclinations at stages two (2.27°) and four (3.57°). The only statistical significance (p.0319) obtained in the analysis was in the position of the right shank. Stage one, two, and three were statistically the same and stage two, three, and four were statistically the same. P values for the other segment inclinations at touchdown were .6914 for the thigh and .4799 for the foot (see Table F-1). P values for differences in leg segmental inclinations at touchdown between boys and girls in this study ranged from .2259 to .3245 (see Table F-2). However, females had greater (0.83° to 10.78°) thigh, shank, and foot inclinations than males for both the right and left legs. The combination of lower magnitude thigh inclination and higher magnitude shank inclination indicates that the limb touches down farther in front of the downward vertical projection of the body's center of gravity than the limb with a combination of higher thigh and lower shank inclination. The finding of the lowest shank inclinations

(83.62°, 91.41°) in the stage four runners may indicate a parallel of the research reported by Dillman (1975) and Wickstrom (1983). They indicated that the more mature and faster runner has a more efficient sequential backward rotation (with respect to the trunk) of the leg just prior to touchdown and has touchdown of the foot closer to the downward vertical projection of the body's center of gravity. The distance between the downward vertical projection of the body's center of gravity and the foot at touchdown will be discussed in more detail later in this chapter.

Leg Drive Interval - Takeoff. At takeoff, smaller magnitudes of segmental inclinations indicated greater backward extension of the thigh and shank segments and greater plantar flexion of the foot. Predicted trends for leg segmental inclinations at takeoff were based on Figure 2 (p. 19). Analysis of the subjects in this study (see Figure 25) yielded a range of p values from .2191 to .7788 among the four stages and between gender groups and some interesting variations on the predicted trends (see Tables F-3 and F-4). The thigh inclination at takeoff was predicted to decrease from stage one to stage two, which did occur in the subjects' left thighs but not in the right thighs. From stage two to stage three the thigh inclination was predicted to increase, but both right and left thigh inclinations decreased in the subjects studied. From stage three to stage four the thigh segment was predicted to decrease, which did occur in the subjects' left thighs but not in the right thighs. In stages two and four the right thigh inclinations were greater (4.84°, 4.42°) than the left thigh inclinations, whereas in

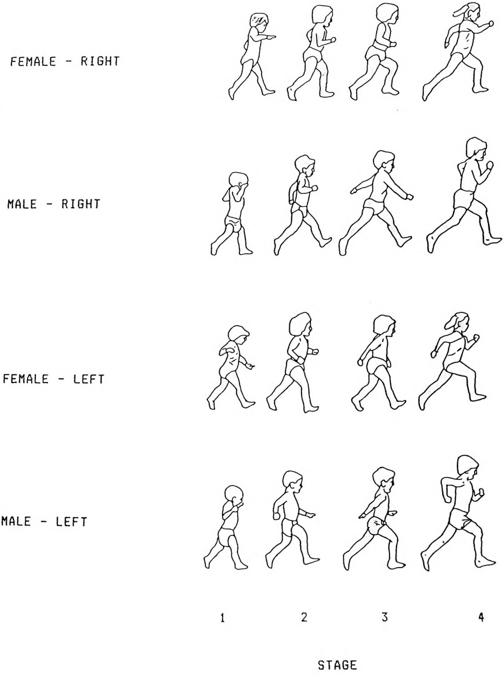


Figure 25. Film tracings of subjects at right and left takeoff.

stages one and three the left thigh inclinations were greater (13.18°, 4.81°) than the right thigh inclinations.

For the shank at takeoff, inclination was predicted to decrease from stage one to stage two, then increase from stage two to stage three. The subjects in the study did follow these predictions. From stage three to stage four the shank inclination was predicted to decrease, which did occur in the subjects' right shank inclinations, but not in the left shank inclinations. The difference in the magnitude of the inclinations between right and left shanks was just the opposite of the thigh inclinations. At stage one and three the right shank inclinations were greater (3.71°, 2.33°) than the left shank inclinations, whereas at stages two and four the left shank inclinations were greater (3.96°, 10.65°) than the right shank inclinations. The leg with the combination of lower thigh inclination and higher shank inclination (as compared to the opposing leg) had greater (7.15° to 6.88°) actual knee angle (shank inclination + (180° - thigh inclination)) than the leg with a combination of higher thigh inclination and lower shank inclination.

Foot inclination at takeoff was predicted to decrease progressively from stage one to stage three then increase from stage three to stage four. Just the opposite occurred for both feet. Foot inclinations progressively increased from stages one to three then decreased from stages three to four. At takeoff, both boys and girls had greater (3.50°, 0.86°) inclinations with the left thighs than the right thighs, but greater right than left inclinations for the shank (2.00°, 6.29°) and foot (11.50°, 8.18°) segments. Similar to touchdown, the females

had greater (0.73° to 27.04°) inclinations of the leg segments than the males at takeoff.

Leg Drive Interval - Maximum Leg Extension. Research on mature running form generally agrees that in most instances maximum leg extension occurs as the foot leaves the ground at takeoff. Research on the development of running described increases in leg extension at takeoff as age (and speed) increased (Clouse, 1959; Dittmer, 1962; Fortney, 1980; and Miyamaru, 1976). The subjects in the present study varied somewhat from the reported trends. Actual maximum leg extension was determined by calculating the greatest knee joint angle: shank inclination + (180° - thigh inclination). The greatest knee joint angle did occur prior to, but increasingly closer to, takeoff as stage increased: stage one = .09 seconds, stage two = .05 seconds, stage three = .02 seconds, stage four = .01 seconds. (See section on temporal analysis for further discussion on this point.) Simultaneous maximum leg extension and takeoff occurred only on the right takeoff for stage three male and left takeoff for both stage four runners.

At actual maximum leg extension both right and left leg segmental inclinations progressively decreased as expected, yet the actual knee joint angle progressively decreased (see Figure 26 and Tables F-5 and F-6). Males had lower (3.14° to 14.34°) segmental inclinations than females, but the females had greater (right = 1.32°, left = 13.07°) actual knee angles. Only the inclinations of the left shanks significantly differed (p.0306) between gender groups. Generally both right and left leg segmental inclinations continued to decrease from

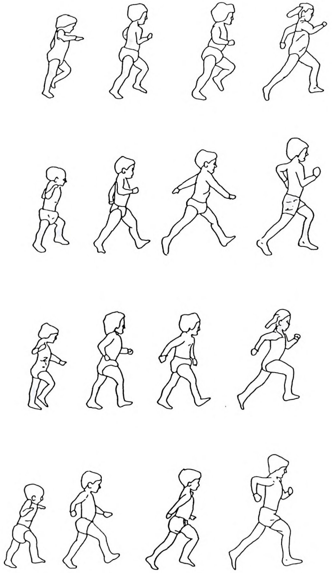


Figure 26. Film tracings of subjects at right and left maximum leg extension.

maximum leg extension to takeoff, but the progressive linear trend among stages for decrease in actual knee joint angle is not present at takeoff as it is at maximum leg extension (see Table 14). Calculation of the actual hip joint angle (trunk inclination + (180° - thigh inclination)) revealed just the opposite trend. Each successive stage resulted in an increase in hip joint angle at takeoff, but this did not coincide with maximum leg extension. Calculation of the actual ankle joint angle (shank inclination + (180° - foot inclination)) revealed greater increases in the angle of plantar flexion between the instant of maximum leg extension and takeoff at stages one (35.64°) and two (25.94°) than stages three (13.18°) and four (13.08°). At maximum leg extension and takeoff the actual ankle angle decreased from stage one to three then increased at stage four.

At maximum leg extension a linear trend of decreasing shank inclinations was observed for stages one through four in both the right and left leg segments. Whereas at takeoff, the shank segments decrease from stage one to two and increase from stage two to three. From stage three to four the right shank inclination decreases and the left shank inclination increases. A partial explanation for the observed differences in segmental inclinations, actual joint angles, and timing between maximum leg extension and takeoff can be found in R. V. Mann's (1981) kinetic analysis of sprinting. He reported that as takeoff was approached, the knee extensors decreased in activity and thus provided protection from hyperextension. The maximum extension of the leg may not occur as the foot leaves the ground at takeoff due to this decrease in knee extension activity. Since the timing for this decrease in knee

Table 14

Comparison of Mean Actual Leg Joint Angles (deg) at Maximum Leg Extension and Takeoff by Stage.

	STAGE 1	2	3	4
HIP JOINT[1]				
MAXIMUM LEG EXTENSION	179.274	189.605	164.208	165.697
TAKEOFF	184.296	189.853	194.951	196.443
KNEE JOINT[2]				
MAXIMUM LEG EXTENSION	181.552	173.014	170.982	162.936
TAKEOFF	155.450	150.850	160.556	159.245
ANKLE JOINT[3]				
MAXIMUM LEG EXTENSION	101.092	96.503	95.66	120.984
TAKEOFF	136.733	122.440	108.845	134.059
TIME LAPSE[4]	.09	.05	.02	.01

1 Actual hip joint angle = trunk inclination + (180° - thigh inclination).

2 Actual knee joint angle = shank inclination + (180° - thigh inclination).

3 Actual ankle joint angle = shank inclination + (180° - foot inclination).

4 Time (s) between maximum leg extension and takeoff.

extensor action depends upon the fine tuning of the nervous system, the degree of nervous system development then may be reflected in the observed and measured differences between maximum leg extension and and takeoff in these young children.

The 100 fps film speed enabled the researcher to 'see' elements of the running cycle that occur too fast for the naked eye to substantiate. In this study, as the stage-one runners approached takeoff they seemed to "lockout" the support knee then ride their momentum forward. The knee of the takeoff support leg would "give" as runners fell onto the opposite leg for support. Even with the addition of the flight phase in stage two, the subjects' extending support leg seemed to cease extension, then they would ride their momentum into flight rather than time maximum plantar flexion for a final push at takeoff. The final push off seemed more evident in stages three and four. These observations suggest questions for future investigation. Where does the extension of the leg segments cease in relation to takeoff? How does the amount and timing of extension relate to neurological development? A kinetic analysis would provide additional insight into these questions.

Trunk Inclination at Touchdown and Takeoff. Trunk inclinations were measured relative to the horizontal as illustrated in Figure 17 (p. 86). The greater the magnitude of the inclination the more upright the trunk position. Statistical analysis of the trunk inclinations at right and left touchdown and takeoff yielded p values ranging from .0808 to .7403 among the four stages and between gender groups (see Tables F-7

and F-8). The inclination values were so similar among the four stages (<4.6°) that one cannot readily see any developmental trend.

At touchdown (Figure 24, p. 110) all runners had lower (1.54° to 3.40°) inclinations (i.e. meaning slightly more forward trunk lean) on the right leg than on the left leg. At takeoff (Figure 25, p. 113) the stage two and stage three runners continued to have lower (0.65°, 3.06°) inclinations on the right leg than on the left leg with just the opposite true for stage one (3.58°) and stage four (1.68°) runners. At takeoff, the trunk inclinations for stage one runners were slightly more (1.31°) forward than at touchdown. Trunk inclinations for stage three performers were slightly more (1.58°) forward at touchdown than at takeoff. Stage two and stage four runners had slightly more (1.06°, 2.83°) forward trunk inclination at right touchdown than at right takeoff with the opposite occurring on the left leg (1.26°, 2.25°).

Females had slightly more (4.00°, 4.17°) forward trunk inclinations than males at both touchdown and takeoff. Both males and females had slightly more (2.49°, 2.60°) forward trunk inclinations at right than left touchdown, with the opposite true at takeoff (0.40°, 0.36°). Trunk inclinations among the subjects were comparable to those reported by Miyamaru (1976) and with the preschool-age children in Brown's (1978) study.

<u>Leg Recovery Interval - Minimum Knee Angle</u>. Developmental trends for thigh and shank segmental inclinations during the recovery interval at minimum knee angle were predicted based on Figure 3 (p. 20). Trends for the foot-segment inclinations were not predicted. Analysis of the

data on subjects in Figure 27 yielded a range of p values from .0266 to .7361 (follow up test for $p<.05$ were nonsignificant) among the stages and between the gender groups (Tables F-9 and F-10). The larger the value of the thigh inclination, the higher was the position of the thigh relative to the supporting surface. The lower the value of the shank inclination, the closer the foot was positioned to the buttock. Whether the value of the foot inclination indicated plantorflexion or dorsiflection depended upon the foot inclination's relation to the shank inclination. Actual knee joint angle was calculated by using the formula of shank inclination + (180° - thigh inclination).

The thigh segment inclination at minimum knee angle was predicted to decrease progressively from stage one to three, then to increase from stage three to four. The right thigh followed this prediction, but the left thigh inclination decreased from stage one to stage two then progressively increased from stage two to stage four.

Shank inclinations at minimum knee angle also were predicted to decrease progressively from stages one to three then to increase from stage three to four. The right shank followed this prediction with the stage four inclination lower (18.30°) than the stage-one inclination. The left shank decreased from stage one to stage two, increased from stage two to stage three, then decreased from stage three to stage four. Again the shank inclination at stage four was lower (18.22°) than the shank inclination at stage one.

Specific predictions were not made for foot inclinations at minimum knee angle. From stage one to stage two both right and left-foot inclinations at minimum knee angle decreased. From stage two to stage

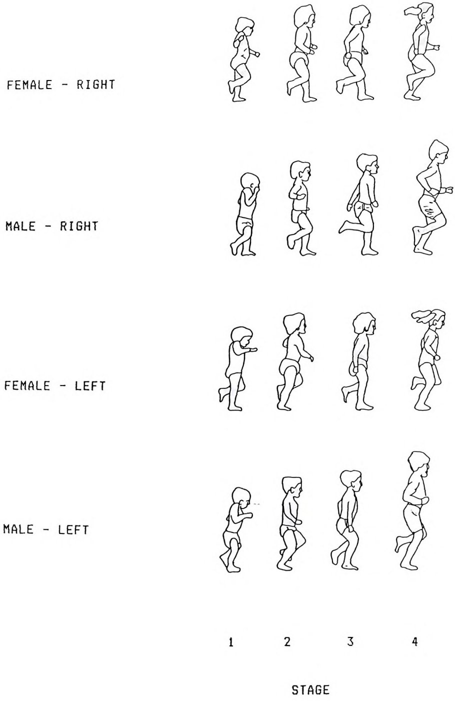


Figure 27. Film tracings of subjects at right and left minimum knee angle.

three the right foot inclination continued to decrease while the left foot inclination increased. The opposite change occurred from stage three to stage four in that the right foot inclination increased and the left foot inclination decreased.

The actual knee joint angle in the right leg followed a progressive linear developmental trend from stage one to stage four. The actual left knee angle progressively increased from stage one to stage three then decreased at stage four to a smaller (14.70°) angle than the stage one runners' actual left knee joint angle.

For both boys and girls there was a developmental trend of a decreasing actual minimum knee joint angle. However, at minimum knee angle, the males had greater (9.56° to 23.75°) thigh, shank, and foot segmental inclinations than the females. Right leg segmental inclinations were greater (2.98° to 9.06°) than left leg inclinations for the females, but for the males the right thigh and the left shank and foot inclinations were greater (2.99° to 5.52°) than the left thigh and right shank and foot inclinations. The actual minimum knee angle was smaller (1.59°, 8.27°) in females than males and the actual minimum knee angle for the right leg was smaller (1.80°) than the actual minimum knee angle for the left leg. This overall developmental trend of an increasingly smaller actual minimum knee joint angle is in agreement with the previously reported research (Clouse, 1959; Dittmer, 1962; rtney, 1964; Glassow et al., 1965; Miyamaru, 1976; Brown, 1978; and rtney, 1980).

Although the segmental inclination measurements at minimum knee le were not statistically significant, it is of note that there were

right-left differences particularly in the shank and foot segments of the stage two and three runners. (See Table F-9.) Right-left differences in the shank and foot segments of the stage one and stage four runners were as much as 17 degrees less than those of the stage two and three runners. Right-left difference in thigh inclinations was approximately 20 degrees in stage two runners and less than four degrees among the stage one, three, and four runners.

Leg Recovery Interval - Maximum Thigh Segment Height. The predicted developmental trend for maximum thigh segment height was based on Figure 4 (p. 21). The larger the inclination value for the thigh segment, the higher the runner was lifting the leg. Analysis of the data from the subjects shown in Figure 28 is presented in Tables F-11 and F-12. Statistical analysis yielded p values of .6856 to .9734 among the four stages and between gender groups. However, a developmental trend was evident.

It was predicted that the thigh segment relative to the horizontal (measured from the distal end) would decrease from stage one through stage three, then increase from stage three to stage four. The data revealed this trend was followed by the subjects in this study. The thigh segment inclinations of the stage four runners were greater (1.39°, 8.10°) than those of the stage one runners. At stages one and two the runners had slightly greater (3.39°, 1.21°) thigh inclinations for their right thighs than their left thighs. The opposite occurred in the stage three and stage four runners (1.51°, 3.32°). The trend of increased thigh segment inclination between stages one and four and

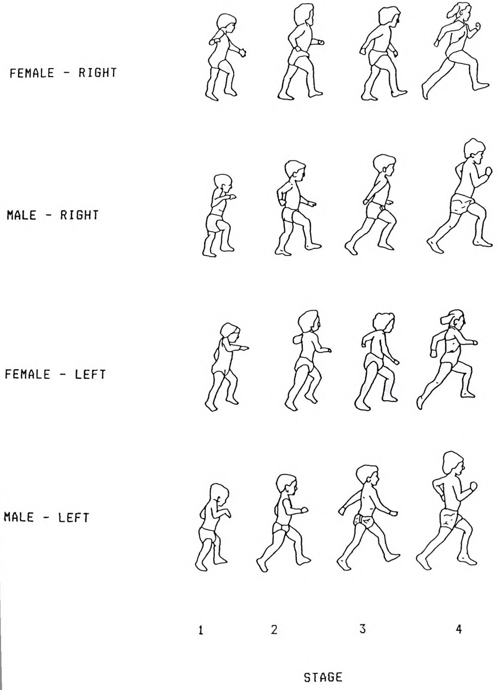


Figure 28. Film tracings of subjects at right and left maximum thigh segment height.

three and four is in agreement with the reported literature (Clouse, 1959; Fortney, 1964; Glassow et al., 1965; Miyamaru, 1976; and Brown, 1978).

Specific predictions for the shank and foot segments at maximum thigh segment height were not made, but the data are interesting. The right shank and foot segment inclinations at maximum thigh segment height increased from stage one to stage two, decreased from stage two to stage three, then increased from stage three to stage four. Magnitudes of the stage four right shank and foot inclinations were greater (12.26°, 18.99°) than those in stage one. The opposite of this pattern was observed in the left shank and foot in that the stage four inclination were less (3.90°, 0.09°) than that in stage one. Left foot inclinations at maximum thigh segment height progressively increased from stage one to stage three, then decreased to the same degree as stage one.

Although not statistically different, gender differences were evident. Thigh and foot segment inclinations for the males were greater (4.39° to 20.94°) than those in females. No trends were found for degrees of shank inclinations. The males had greater (10.16°) inclinations in the left shank than in the right, and the females had greater (6.49°) inclinations in the right shank than in the left. Left-right differences in the thigh segments were less than one degree for both genders. Left-right differences in foot segment inclinations were greater in males (7.30°) than females (4.12°).

Arm Segment Inclinations. Humerus and forearm inclinations were measured from the distal end of the segment, counterclockwise relative to the horizontal at the maximum forward and backward positions of the humerus (see Figure 21, p. 90). Predictions for the humerus and forearm inclinations at maximum forward position were based on the film tracings in Figure 5 (p. 23). At the maximum forward position the inclination of the humerus was predicted to decrease progressively from stage one to stage three, then increase from stage three to stage four. The left humerus followed this prediction with the stage four inclination being greater (6.89) than that for the stage one runners. The degree of inclination of the right humerus did decrease from stage one to stage two, but then progressively increased in degree of inclination from stage two to stage four. The degree of inclination of the stage four humerus was slightly less (4.80) than that of stage one. The forearms at maximum forward position were predicted to decrease progressively in inclination from stage one to stage three then increase inclination from stage three to stage four. Both right and left forearms followed this prediction.

Predictions for the humerus and forearm inclinations at maximum backward position were based on the film tracings in Figure 6 (p. 24). At the maximum backward position the inclinations of the humerus were predicted to decrease from stage one to stage two, to increase from stage two to stage three, and to decrease from stage three to stage four. Both the right and left humeri decreased progressively in inclination from stage one to stage four. The forearm at maximum backward position was predicted to decrease progressively from stage one

to stage four. The right forearms progressively decreased from stage one to stage three, then increased in inclination, but remained less (16.28°) than that in the stage two. The inclinations of the left forearms increased from stage one to stage two, decreased from stage two to stage three, then decreased but remained lower (2.69°) than the stage one inclination. This would be the expected trend considering the position and action of the humerus. Statistical analysis of the data yielded p values of .0018 to .5422 among the four stages with only the right forearm significant when the right humerus was in the maximum backward position (see Figures 29 and 30 and Table F-13). At maximum humerus backward position the right forearm inclinations of stages one and two were statistically different (p.0018) from those of stages two, three, and four. Among the stages, the range of humerus motion decreased from stage one to stage two and three then increased at stage four. The range of stage four runners was greater (37.26°) than stage one runners. The stage two through stage four trend is in agreement with the findings of Miyamaru (1976).

It is interesting to note the left-right differences in the humerus range of motion (3.12° to 20.00°) across stages (see Table F-13). From stage one the greater range shifts from right to left and back to right with the largest right-left differences in stage two (20.00°) and three (19.37°). This pattern is reflective of what is happening with the humerus inclinations. That is, the greater the humerus range, the greater the magnitude of the humerus inclinations at the maximum forward position and the maximum backward position.

P values of .1889 to .9626 were obtained between gender groups.

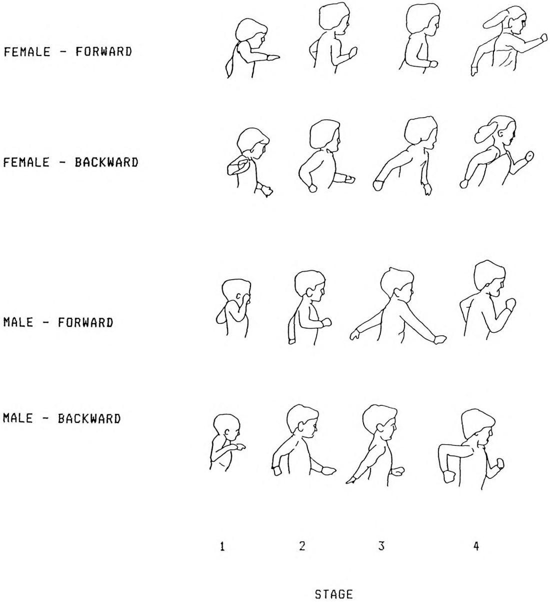


Figure 29. Sagittal film tracings of subjects at right humerus maximum forward and maximum backward.

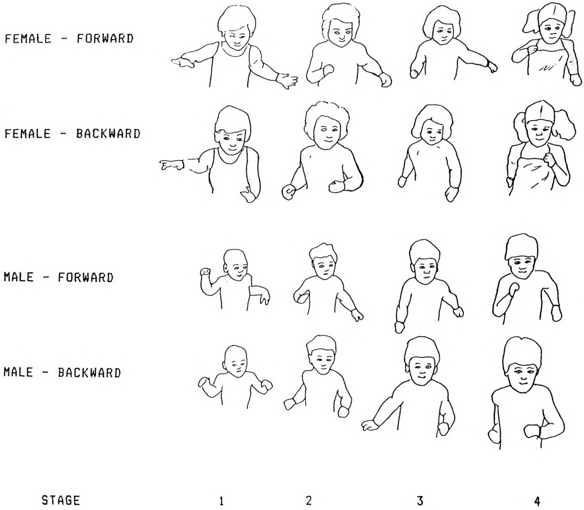
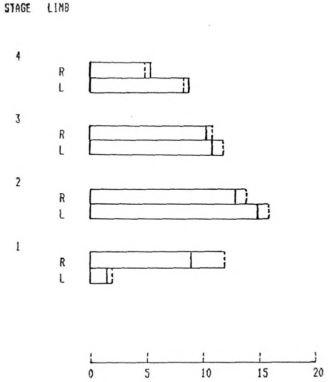


Figure 30. Frontal film tracings of subjects at right humerus maximum forward and maximum backward.

Females had larger (13.03°, 11.49°) ranges of motion and smaller (2.29° to 13.58°) forearm inclinations at both the forward and backward positions (see Table F-14). These observations raise the question of when, during the development of running skill, does arm motion become less of a reaction to and more of a contribution to force production? A kinetic study of developmental stages of running is needed to answer this question. Also, might there be some better way, than that used in the present study, to quantitatively analyze the qualitative changes observed in arm movements?

Body C.O.G. - Foot Distance at Touchdown.

Two previous studies on the development of running in children have investigated the distance between the downward vertical projection of the body's center of gravity and the foot at touchdown (Dittmer, 1962; Mersereau, 1974). The analysis of this distance for the subjects in the present investigation, yielded p values of .6552 and .4156 among the running stages and between gender groups. However, the data provide some insight to the conflicting findings of the previous two studies (see Figure 31 and Tables F-15 and F-16). Note the data are presented as actual measurements (cm), and as percent of standing height. From stage one to stage two the distance between the downward vertical projection of the body's center distance for the left foot of stage one runners was less (10% standing height) than for the right foot, with the opposite true for stage two (2% standing height), three (1% standing height), and four (3% standing height) runners. Males placed the right



Key: (|) = actual displacement in cm
(¦) = percent of standing height
L = left, R = right, H = humerus, F = forearm

Figure 31. Distance between downward vertical projection of body center of gravity and foot at right and left touchdown.

foot closer (2% standing hieght) to the downward vertical projection of the body's center of gravity than the left foot, with the opposite (4% standing height) true for females.

Keeping in mind that the developmental stages are age related, but not age dependent, the research by the Early Childhood Motor Skills Development Study (1985), Fountain, Ulrich, Seefeldt and Haubenstricker (1981), and Seefeldt and Haubenstricker (1982) gives evidence of the stage and age relationship in running development. Dittmer's (1962) subjects ranged in age from 5 to 11 years, an age span where the majority of the children are stage three and stage four runners. Mersereau's (1974) subjects were 22 and 25 months old, an age span where children are generally stage one and stage two runners. Considering the age differences of the subjects in these two previous studies (Dittmer, 1962; Mersereau, 1974), the data reported in the developmental stage studies (Early Childhood, 1985; Fountain, Ulrich, Seefeldt and Haubenstricker, 1981), and the trend in the present study, the findings reported by Mersereau (1974) may not be the opposite of the findings reported by Dittmer (1962), but the two previous studies may be at opposite ends of a developmental trend. Further research is needed to verify the trend reported.

<u>Sequence of Peak Angular Velocity in the Legs</u>.

Only one previous study of the development of running in young children investigated the sequence of peak angular velocities of leg action. Predictions for the present study were made based on Fortney's

(1980) data on limb joint peak angular velocities of 2-, 4-, and 6-year old children. The present study investigated the limb segment peak angular velocities of children ranging in age from 16 to 56 months who were categorized according to developmental stage of running skill. The reader is cautioned that a direct comparison between Fortney's (1980) results and those of the present study is not possible due to differences in the biomechanics software programs used in the two studies (Fortney, personal communication, April 14, 1987) as well as the difference in subject classification (age versus running stage). However, the two studies provide an interesting parallel.

Drive interval. A thigh, shank, foot sequence of segment peak angular velocity was predicted for leg action during the midsupport and takeoff phases of the drive interval. This arrangement was selected since Fortney (1980) reported the majority of her 2-year olds had a simultaneous hip and knee, then ankle sequence, and the majority of her 4- and 6-year olds had a hip, knee, ankle succession of joint peak angular velocity. In the present study the stage one runners had thigh, shank, foot segment sequences except for the male's left leg which sequenced shank, thigh, foot. The stage three and stage four runners had shank, thigh, foot segment sequences except for the stage three female's left leg which sequenced thigh, foot, shank. The stage two male had a shank, thigh, foot sequence of segment peak angular velocity, but the female had a right leg sequence of foot, thigh, shank and a left leg sequence of foot, shank, thigh. Several interesting observations can be made from the sequences reported in Table 15.

Table 15

Sequence of Leg Segments Peak Angular Velocities for Leg Extension During the Drive Interval (ms = midsupport phase, to = takeoff phase).

STAGE	GENDER	RIGHT LEG	LEFT LEG
1	M	thigh (to), shank (to), foot (to)	shank (ms), thigh (ms), foot (to)
	F	thigh (ms), shank (to), foot (to)	thigh (ms), shank and foot (to)
2	M	shank (ms), thigh (to), foot (to)	shank (ms), thigh (ms), foot (to)
	F	foot (ms), thigh (ms), shank (to)	foot (ms), shank (ms), thigh (ms)
3	M	shank (ms), thigh (to), foot (to)	shank (ms), thigh (to), foot (to)
	F	shank (ms), thigh (to), foot (to)	thigh (ms), foot (ms), shank (to)
4	M	shank (ms), thigh (to), foot (to)	shank (to), thigh (to), foot (to)
	F	shank (to), thigh (to), foot (to)	shank (to), thigh (to), foot (to)

In the less mature runners, more of the leg segments peak during the midsupport phase of the drive interval whereas in the more mature runners, more leg segments peak during the takeoff phase of the drive interval. The sequence order seems to shift from thigh, shank, foot, in the immature running form of stage one, to shank, thigh, foot, in the mature running form of stage four. And, the greatest inconsistency in sequences is found in the stage two runners. Could these observations be reflective of neurophysiological developmental changes?

Recovery Interval. A shank, thigh, foot sequence of segment peak angular velocity was predicted for leg action during the follow through and forward swing phases of the recovery interval. This arrangement was selected since Fortney (1980) reported the majority of all her subjects had a knee, hip, ankle sequence of joint peak angular velocity (see Table 16). In the present study all runners except the stage two male had a shank, thigh, foot sequence of segment peak angular velocity. The only other near variation was seen in the stage one female, whose foot segment velocity actually peaked during the foot descent phase. Two points are worthy of note here. The high speed of the film (100 fps) revealed the stage one female was beginning to move into the transition period between stage one and two (See section on temporal analysis for detail.). A question arises then. In qualitative assessment, both the stage one and stage two males were classic examples of their respective running development stages. The sequences of segment peak angular velocities for the stage one male were consistent for both legs whereas the sequences were inconsistent for the stage two male. Might the stage

Table 16

Sequence of Leg Segments Peak Angular Velocities for Leg Flexion During the Recovery Interval (ft = follow through phase, fs = forward swing phase).

STAGE	GENDER	RIGHT LEG	LEFT LEG
1	M	shank (fs), thigh (fs), foot (fs)	shank (fs), thigh (fs), foot (fs)
	F	shank (fs), thigh (fs), foot (fd)*	shank (fs), thigh (fs), foot (fd)*
2	M	shank (fs), foot (fs), thigh (fs)	foot (fs), shank (fs), thigh (fs)
	F	shank (fs), thigh (fs), foot (fs)	shank (fs), thigh (fs), foot (fs)
3	M	shank (fs), thigh (fs), foot (fs)	shank (fs), thigh (fs), foot (fs)
	F	shank (fs), thigh (fs), foot (fs*)	shank (fs), thigh (fs), foot (fs)
4	M	shank (fs), thigh (fs), foot (fs)	shank (ft), thigh (fs), foot (fs)
	F	shank (fs), thigh and foot (fs)	shank (ft), thigh (fs), foot (fs)

* Indicates actual peak angular velocity occurred during foot descent phase.

one female's foot peak velocity occurring in the foot descent phase be a possible indication of her moving into the right-left inconsistency observed in the stage two male? A second point of note, since the stage two female, instead of having an inconsistent sequence of segment peak angular velocity, had the consistent right-left sequence found in the stage one male and the stage three and four runners. On the day of filming the stage two female ran in a stage three form during one of her trials, a common occurrence among children in transition between classic running stages. Might her consistency in segment sequence of peak angular velocity be an indication that she had begun the transition into a stage three running form? These questions can only be answered through further research on peak angular velocities in the developing runner.

Drawn Midline - Limb Segments Centers of Gravity Distance

Previous research on running skill development has been almost entirely conducted from the sagittal plane (side view) and limited to leg action. In addition to the sagittal plane (side view) film analysis, the present study also used frontal plane (front view) film to explore an approach to investigating the rotary movements of the arms and legs about the vertical axis of the body. Four specific events within a complete running cycle for each leg were selected for analysis: touchdown, takeoff, minimum knee angle, and maximum thigh segment height. For each subject, the selected film frames were projected onto graph paper (10mm to a centimeter) in order to trace a stick figure of

the subject's body position to be analyzed. A midline (determined by locating the midpoint between the two hip joints, then by drawing a line from, and perpendicular to, the supporting surface up through the midpoint between the hip joints, and continuing to equal head height, as illustrated in Figure 23, p. 93) was drawn over each stick figure. Using a Walton template (Walton, 1970), segmental centers of gravity were located and marked for each limb segment. The distance between each segment center of gravity, midpoint between the two shoulder joints, and the drawn midline was measured, multiplied by the film conversion factor, and then recorded for later statistical analysis. Data from the support and nonsupport sides of the body for the right and left touchdown, takeoff, minimum knee angle, and maximum thigh segment height were then analyzed. The statistical analysis a range of p values from .0755 to .9954 among the four stages and between gender groups. When the measurements are considered as a percentage of standing height, evidence of some possible developmental trends begin to appear among the four running stages. By comparing the right and left support side foot with the nonsupport side hand, as well as the nonsupport side foot with the support side hand, one can begin to see the rotary reactions of the limbs.

At touchdown (Figure 32), several trends were apparent in the data (see Table F-17). Most obvious was that the support foot at right touchdown was closer (stage 1 = 2%, stage 2 = 5%, stage 4 = 2% standing height) to the drawn midline than the support foot at left touch down for all stages except three (1% standing height). The greatest (5% standing height) variation between support foot at left and right

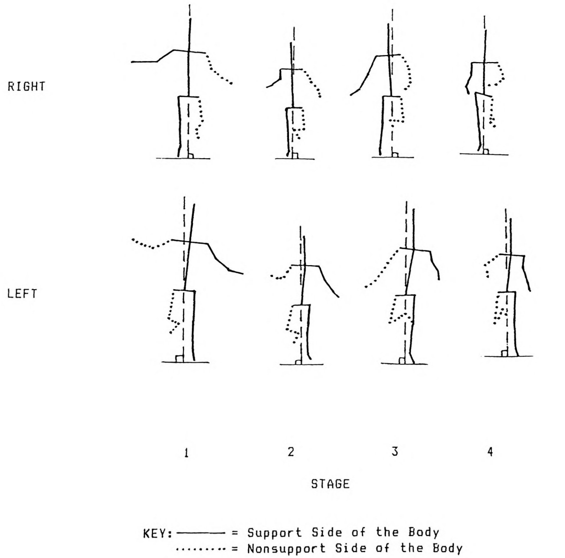


Figure 32. Frontal film stick figures for comparison of the distance between the drawn midline and the segment centers of gravity at right and left touchdown.

touchdown was in stage two. The support foot position in relation to the drawn midline did not show a trend over the four stages, but the opposing hand moved progressively closer (23% to 6.5% standing height) to the drawn midline across stages. The nonsupport foot moved closer to, then farther away (4.5% to 4% to 2.5% to 6% standing height) from the drawn midline across the stages while the opposing hand moved closer (34% to 14.5% standing height) to the drawn midline across the stages. The right touchdown nonsupport side hand was closer to the drawn midline than the left touchdown nonsupport side hand in all stages except stage two (right stage 1 = 10%, stage 3 = 5%, stage 4 = 4%, left stage 2 = 3% standing height). The same, but opposite, overall pattern could be seen the in the nonsupport side feet and support side hands. At left touchdown the nonsupport leg seemed to be in position for greater outward rotation than the nonsupport leg at right touchdown for stages one, two, and three. Limb counterrotations seemed more symmetrical in stages one and four than stages two and three, but the limbs were much closer to the midline in stage four than the other three stages. Shoulder variation from the drawn midline, was toward the touchdown side of the body across all stages and was greatest (3% standing height) in stage three. The only item of note between gender groups was that females seemed to have slightly less (.005% standing height) shoulder variation than males (see Table F-18).

At takeoff (Figure 33), no real trend was noted in the support or nonsupport leg segments (see Table F-19). The hands moved closer to the drawn midline (support side = 26% to 5%, nonsupport side = 31% to 13% standing height) across stages with greater variations ($\overline{X}$ = 9.5%

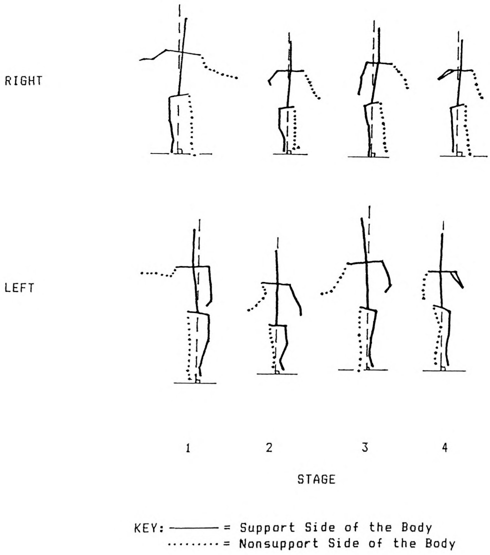


Figure 33. Frontal film stick figures for comparison of the distance between the drawn midline and the segment centers of gravity at right and left takeoff.

standing height) on the nonsupport side in stages two and three than in stages one and four ($\bar{X}$ = 4.5% standing height). No noticeable trends were observed between gender groups (see Table F-20).

At minimum knee angle (Figure 34), the position of the nonsupport leg was observed to move closer (thigh = 11% to 4%, shank = 13% to 5%, foot = 12% to 1% standing height) to the drawn midline across stages indicating less outward rotation of the swing leg (see Table F-21). This decrease in outward rotation was evident in both right and left minimum knee angle and would agree with Wickstrom's (1983) observations. Again, no real differences were noted in the position of the support foot, and arm position moved closer (e.g. support side forearm = 24% to 15%, nonsupport side forearm = 23% to 15% standing height) to the body across stages. As at touchdown and takeoff, there seemed to be slightly more right-left variability in stages two and three. The only point of note between boys and girls was that the support foot of the males was slightly closer (left = 1%, right = 2% standing height) to the drawn midline than that of the females for both right and left minimum knee angle (see Table F-22).

At maximum thigh segment height (Figure 35), the swing leg moved closer (thigh $\bar{X}$ = 8.5% to 5.5%, shank $\bar{X}$ = 10% to 4.5%, foot $\bar{X}$ = 11% to 6% standing height) to the drawn midline and there was a reduction in foot flair (abduction) across stages (see Table F-23). The support side foot and arm moved closer (foot $\bar{X}$ 4.5% to 3%, hand $\bar{X}$ 21% to 7% standing height) to the drawn midline across the stages. Between gender groups, the support and nonsupport foot were closer ($\leq$1% standing height) to the drawn midline at right maximum thigh segment height than at left maximum

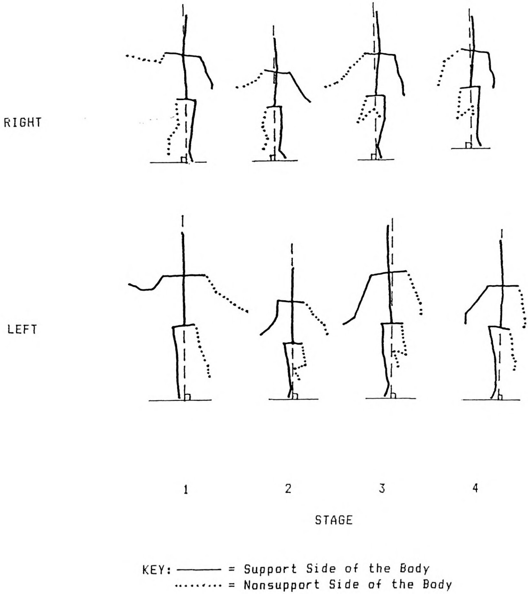


Figure 34. Frontal film stick figures for comparison of the distance between the drawn midline and the segment centers of gravity at right and left minimum knee angle.

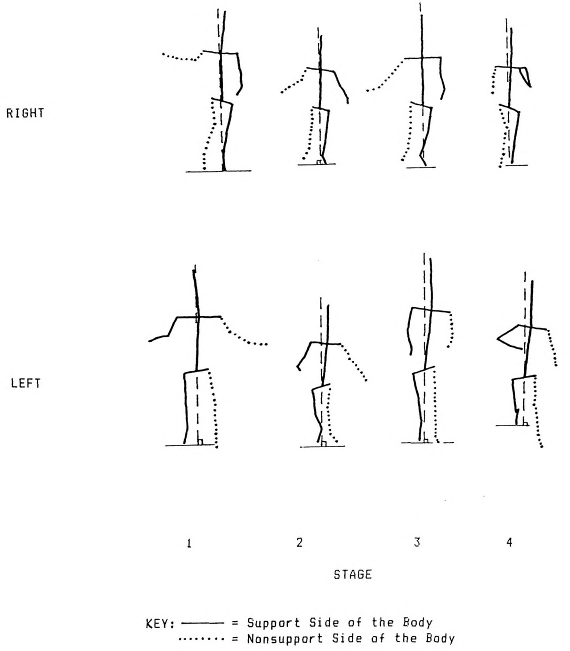


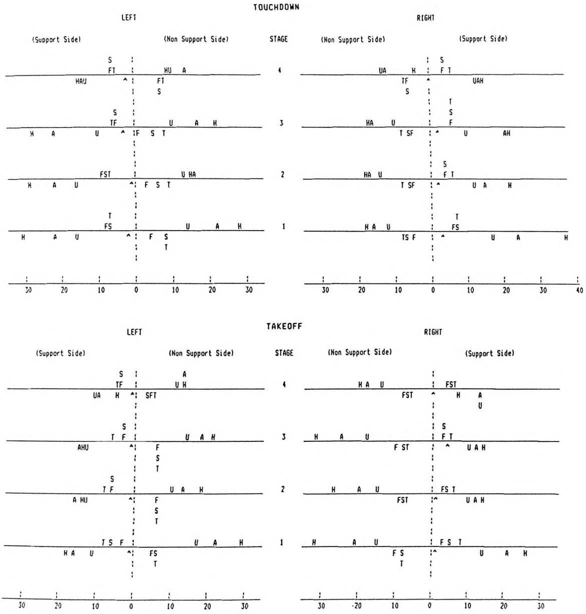
Figure 35. Frontal film stick figures for comparison of the distance between the drawn midline and the segment centers of gravity at right and left maximum thigh segment height.

thigh segment height except for males' support side where the left foot was closer (1% standing height) than the right (see Table F-24).

Figures 36 and 37 offer a graphic illustration of the counter rotary action of the limbs at each of the selected events of touchdown, takeoff, minimum knee angle, and maximum thigh segment height. Position of limb segment centers of mass are indicated as if one were viewing the event from directly overhead the runner. Note that the changes in support foot position between touchdown and takeoff and minimum knee angle and maximum thigh segment height are due to the measurement method for determining the drawn midline location and thus reflects the amount of lateral shifting in the hips as the runner moved from one event to the next. Across all stages, the closer the foot was located to the drawn midline, the farther away was the opposing hand, but the distances decreased across the stages. As observed in the other variables within this study, there seemed to be greater left-right event variability in stage two and stage three runners than in stage one and stage four runners. Sagittal (side) and frontal (front) view analyses of paths of the total body center of gravity might give a clearer understanding than single planar analysis of the development and refinement of running skill.

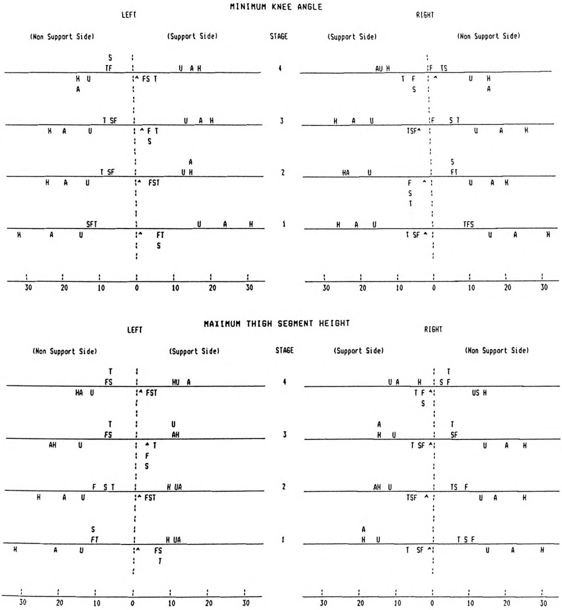
Temporal Analysis.

Based on previous research it was predicted that during one running cycle for each leg, the time in support would decrease while the time in flight would increase at each successive stage. This would also mean



KEY: Limb segment location represented as a percentage of standing height.
H = Hand, A = Forearm, U = Humerus, F = Foot, S = Shank, T = Thigh,
^ = Shoulder Variation.

Figure 36. Graphic illustration of limb segment locations for right and left touchdown and takeoff.



KEY: Limb segment location represented as a percentage of standing height.
H = Hand, A = Forearm, U = Humerus, F = Foot, S = Shank, T = Thigh,
^ = Shoulder Variation.

Figure 37. Graphic illustration of limb segment locations for right and left minimum knee angle and maximum thigh segment height.

the total time in support would decrease while total time in nonsupport would increase at each successive stage. Statistical analysis of this data in terms of time in seconds and as a percent of the total cycles for the subjects in the present study yielded p values ranging from .0390 to .0035 for stage effect and from .3384 to .8754 for gender effect (see Tables F-25 to F-32). P values <.05 were nonsignificant in follow up testing. The developmental trend across the stages observed in Tables F-25, F-26, F-29, and F-30 does follow the reported research (Beck, 1966; Brown, 1978; Dittmer, 1962; Glassow et al., 1965; Mersereau, 1974; Miyamaru, 1976; Smith, 1977; Vilchkovsky et al., 1973; and Wickstrom, 1983). Males spent more time in support (.01s, .04s) and nonsupport (.35s, .17s) on each side than females (Table F-27), but females spent slightly more time (.002s) in nonsupport than males (Table F-28). In terms of percentages, right-left differences for gender groups were mixed (Table F-31). Overall, males spent a greater (1.25) percent of the total right-left cycles in support than females and conversely, the females had a greater (2.75) percent of the total right-left cycles in nonsupport (Table F-32).

One surprise and another possible explanation of an observed phenomenon emerged among the data. The surprise occurred in the stage one female runner. Two days prior to the filming, and during the filming session itself, she moved as a very highly motivated stage one runner with no visible flight. However, the film revealed .04 seconds of flight in her run. This raised the question of how long must flight be before it becomes visible to the naked eye?

One often observes an unevenness to the running of young children,

particularly those in stages two and three. A possible explanation for this unevenness becomes evident when one examines the temporal qualities of the run cycle for each leg. Taken as a total (both sides of the body and subjects for each stage averaged together), the developmental trend in support and nonsupport is smooth (see Figure 38). By separating the subjects within each stage the picture begins to change (see Figure 39). Females have less (19, 5) percent of cycles in support in stages one and four, where males have less (3, 16) percent in support in stages two and three. By further examining the percent of support and nonsupport for each leg of each subject at each stage, the picture becomes even clearer (Figure 40). In stages one and two there is noticeable difference in the percent of each leg cycle spent in support with males having greater (7, 4) percent in support on the left leg and females having greater (7, 5) percent support on the right leg. Although the difference is still observed in stages three and four, the magnitude of the variation is less (1% to 3%) For both gender groups the left leg had greater (2) percent of support in stage three and the right leg has greater (2) percent of support in stage four.

By examining the time breakdown for five selected periods within the cycle for each leg one can further inspect the variations. Table E-24 gives the time in seconds for each leg from: (a) touchdown to maximum leg extension, (b) maximum leg extension to takeoff, (c) takeoff to minimum knee angle, (d) minimum knee angle to maximum thigh segment height, and (e) maximum thigh segment height to touchdown. There were more occurrences of greater (>.02s) right-left variation in stage two than in the other three stages. A developmental trend can also be noted

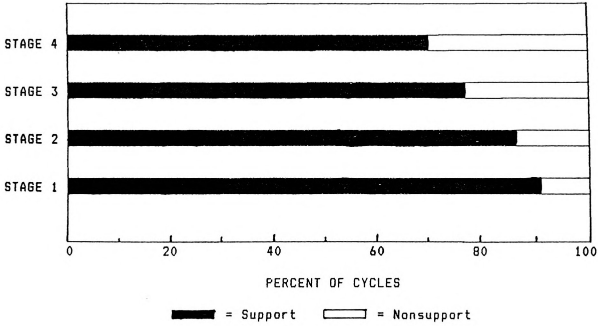


Figure 38. Percent of total cycles in support and nonsupport by stage.

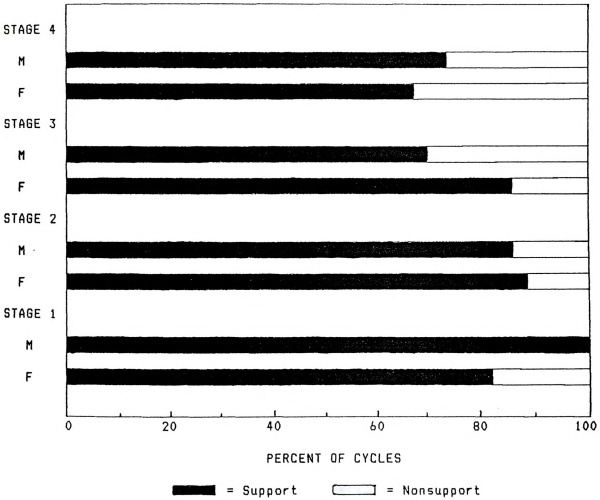


Figure 39. Percent of total cycles in support and nonsupport by stage and gender.

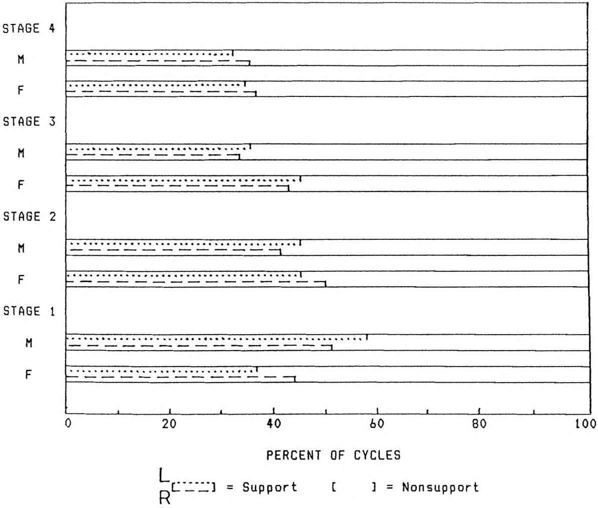


Figure 40. Percent of right and left cycles in support and nonsupport by stage and gender.

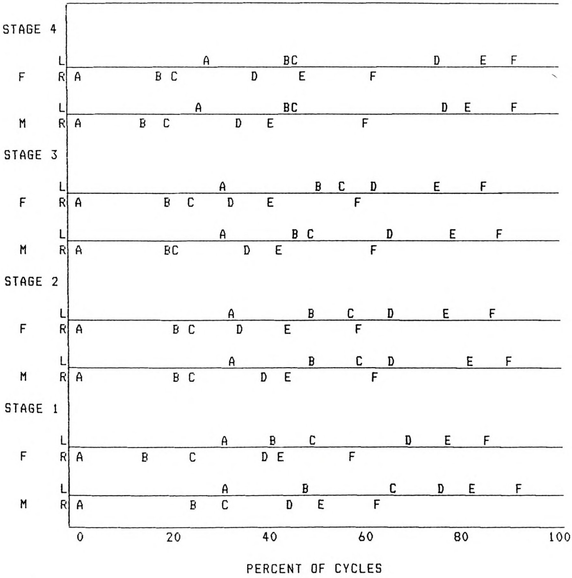
in the maximum leg extension to takeoff timing, which decreased as stage increased. Figure 41 illustrates the points of occurrence for the selected events for each leg for each subject represented as percent of the time for the combined cycles. The unevenness in the right-left leg cycles were more evident in the stage two runners. One must ask then, would further research involving greater numbers of children in each running stage reveal the same temporal variations? If the variations would prove common to the stage two runners, what is the relationship with the development of balance ability and neurophysiological maturation?

Limb Segment Displacements

Both linear displacement (centimeters) and angular displacement (radians and degrees) data for limb segment centers of mass were analyzed. The running cycle for each leg was divided into four periods for the analysis of leg segments displacement:

1. touchdown to takeoff,
2. takeoff to minimum knee angle,
3. minimum knee angle to maximum thigh segment height, and
4. maximum thigh segment height to touchdown.

One forward-backward limb swing was analyzed for arm segments. Angular displacement values are tabled in both radians and degrees, however only the latter are included in the discussion and related figures.

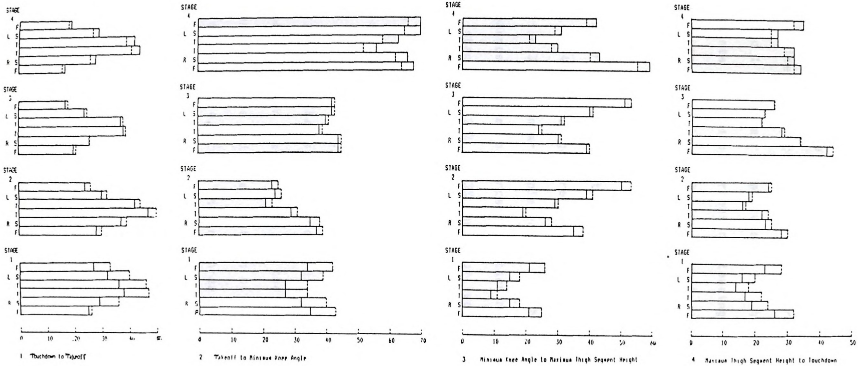


KEY: A = Touchdown
B = Maximum Leg Extension
C = Takeoff
D = Minimum Knee Angle
E = Maximum Thigh Segment Height
F = Touchdown

Figure 41. Point of occurrence for selected events within one running cycle for each leg by stage and gender.

Linear Displacement of Centers of Mass of Leg Segments. Analysis of linear displacements for centers of mass for leg segments yielded p values of .0638 to .8870 for stage effect and .0532 to .8853 for gender effect (see Tables F-33 and F-34). However, a graphic illustration of the data from Table F-33 provides further insight into the development of running skill (see Figure 42). Data are illustrated as actual measurement (cm), and as a percent of standing height. The period 1 portion of the graph (touchdown to takeoff) shows a nearly symmetrical configuration for each stage with stage two displaying some left-right limb segment variation. In the period 2 portion of the graph (takeoff to minimum knee angle) stages one, three, and four remained fairly symmetrical for right-left limb segment displacements with the most obvious right-left differences in stage two. In period 3 of the graph (minimum knee angle to maximum thigh segment height) stage one seemed to remained almost symmetrical. Stages two and three had greater (8% to 15% standing height) linear displacements of centers of mass of the left leg segments while stage four had greater (7% to 16% standing height) linear displacements of centers of mass of the right leg segments. In period 4 of the graph (maximum thigh segment height to touchdown), right-left linear displacements of centers of mass of leg segments appeared fairly symmetrical with slightly greater (4% to 18% standing height) linear displacements of centers of mass for the right limb segments across all four stages. Again, the greatest (6% to 18% standing height) right-left variations occurred in stages two and three.

Looking at the linear displacements of the centers of mass of the leg segments in terms of a percent of standing height enables one to



Key: (|) = actual displacement, (¦) = percent of standing height.
L = left, R = right, F = foot, S = shank, T = thigh.

Figure 42. Linear displacement (cm and percent of standing height) of centers of mass of leg segments during one running cycle for each leg.

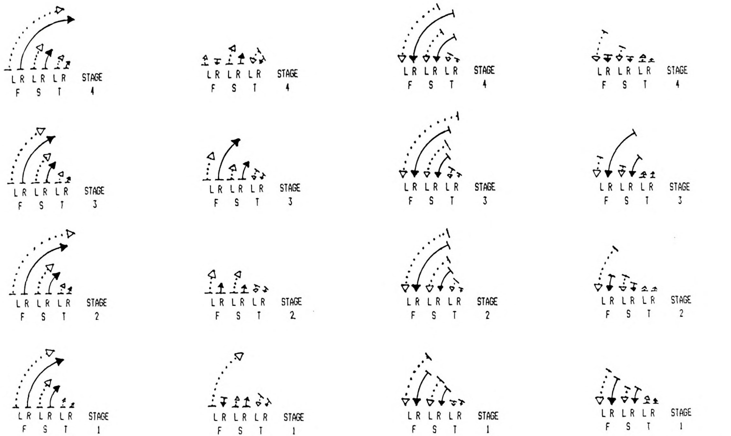
compare performance without considering any differences that might otherwise be reflected by stature differences among subjects. During period 1 the linear displacements for the centers of mass of the leg segments in terms of percent of standing height ranged from 26% to 47% for stage one, 26% to 50% for stage two, 18% to 39% for stage three, and 16% to 41% for stage four. During period 2 the linear displacements for the centers of mass of the leg segments in terms of percent of standing height ranged from 34% to 43% for stage one, 23% to 39% for stage two, 30% to 45% for stage three, and 52% to 66% for stage four. During period 3 the linear displacements for the centers of mass of the leg segments in terms of percent of standing height ranged from 11% to 26% for stage one, 20% to 53% for stage two, 24% to 53% for stage three, and 21% to 55% for stage four. During period 4 the linear displacement for the centers of mass of the leg segments in terms of percent of standing height ranged from 18% to 32% for stage one, 17% to 30% for stage two, 22% to 44% for stage three, and 25% to 32% for stage four. Through periods 1-3, stages two and four runners had a greater (13% to 34%) range of linear displacements for the center of mass of the leg segments than stages one and three in terms of percent of standing height. During period 4, stages one and three had a greater (14%, 22%) ranges of linear displacements for the centers of mass of the leg segments than stages two (13%) and four (7%) in terms of percent of standing height.

Between gender groups, in terms of both actual and percent of standing height (Table F-34), males had greater (1% to 13% linear displacements for the centers of mass of the leg segments than females during periods 1, 2, and 4. Females had greater (1% to 6%) linear

displacements for the centers of mass of the leg segments than males during period 3. The same general pattern was observed in the magnitude of right-left variations in linear displacements for centers of mass of the leg segments; right greater (0% to 7%) than left for periods 1, 2, and 4 (except for males' left thighs were 1% to 2% greater than the right thighs in periods 1 and 2), and left greater (0% to 5%) than right for period 3.

Angular Displacement of Leg Segments. Analysis of angular displacements for leg segments yielded p values of .4823 to .9567 for stage effect and .1824 to .9951 for gender effect (see Tables F-35 and F-36). Figure 43 illustrates the angular displacements for each stage in Table F-35, which were measured from the distal end of the limb segment, counterclockwise relative to the horizontal.

During period 1 (touchdown to takeoff) the thigh segment increased in angular displacement across stages while the shank segment decreased. The angular displacement of the foot segments increased from stages one to two, decreased from stages two to three and increased again from stages three to four. During period 2 (takeoff to minimum knee angle), angular displacement of the thigh segment decreased from stages one to two, then increased progressively from stages two to four. The angular displacement patterns for the shank were the opposite for the right and left segments. The right shank decreased, then increased, then decreased, where the left shank increased, then decreased, then increased in angular displacement across the stages. For stage two the left shank had greater (-21.21°) angular displacement than the right,



1 = Touchdown to Takeoff

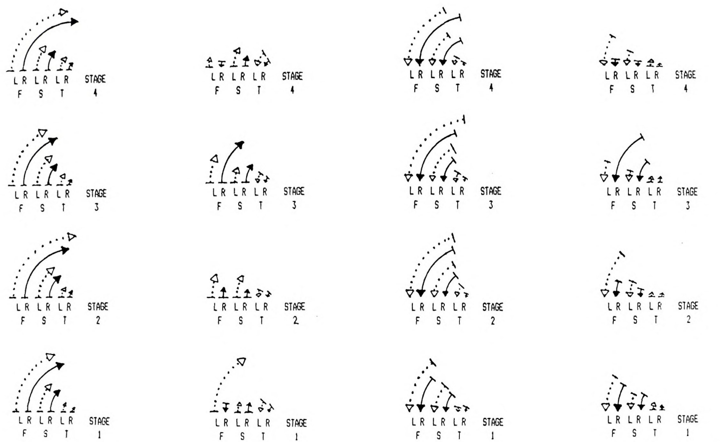
2 = Takeoff to Minimum Knee Angle

3 = Minimum Knee Angle to Maximum Thigh Segment Height

4 = Maximum Thigh Segment Height to Touchdown

Key: F = foot, S = shank, T = thigh, L = left, R = right. Arrow indicates direction of displacement.

Figure 43. Angular displacement (deg) of leg segments during one running cycle for each leg.



1 = Touchdown to Takeoff

2 = Takeoff to Minimum Knee Angle

3 = Minimum Knee Angle to Maximum Thigh Segment Height

4 = Maximum Thigh Segment Height to Touchdown

Key: F = foot, S = shank, T = thigh, L = left, R = right. Arrow indicates direction of displacement.

Figure 43. Angular displacement (deg) of leg segments during one running cycle for each leg.

whereas in stage three the right shank had greater (-18.42°) angular displacement than the left. The magnitudes of the right-left shank differences are much smaller in stages one (-4.31°) and four (-9.99°).

Angular displacements of the foot segments were different for each stage during period 2. For stages one and four the right foot dorsiflexed and the left foot plantar flexed. The angular displacement (disregarding direction) was greater (stage 1 = 51.62°, stage 4 = 0.51°) in the left foot than in the right. In stages two and three both feet plantar flexed with greater (-4.86°,-44.96°) angular displacements in stage three. The left foot had greater (-11.23°) angular displacement in stage two, whereas the right foot had greater (-28.75°) angular displacement in stage three.

During period 3 (minimum knee angle to maximum thigh segment height), the right-left angular displacement patterns differed across the stages. The right thigh increased its angular displacement progressively from stages one to three, then decreased from three to four. The left thigh increased its angular displacement from stages one to two, then progressively decreased from stages two to four. The right shank and foot segments progressively increased in angular displacement from stages one to four, whereas the left shank and foot segments progressively increased in angular displacement from stages one to three, then decreased from stage three to four. Left shank and foot segments had greater (3.29° to 11.71°) angular displacements across stages one to three, whereas the right shank and foot segments had greater angular (13.44°, 13.82°) displacements in stage four.

During period 4 the right-left limb angular displacement patterns

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were different. The right thigh progressively decreased its angular displacement across the stages, whereas the left thigh progressively decreased its angular displacement from stages one to three then increased from stage three to four. The right shank and foot segments decreased, then increased, then decreased across the stages, whereas the left shank and foot segments increased, then decreased, then increased across the stages. Angular displacements for the right shank and foot segments were greater (5.8° to 27.59°) than those for the left shank and foot in stages two and four, but the opposite was true for stages three (left greater (31.02°, 42.94°) than right). For stage one the left-right angular displacements were mixed for the shank and foot segments.

There were no evident trends for boys and girls except during period 3 (minimum knee angle to maximum thigh segment height). Here the females had greater (0.15° to 15.85°) angular displacements than the males, but the right-left differences were mixed.

Linear Displacement of Centers of Mass of Arm Segments. Humerus and forearm segments for each arm were evaluated from the maximum forward position of the humerus to its maximum backward position. Analysis of the linear displacement of centers of mass of arm segments data yielded p values of .7745 and .9373 for stage effect and .8908 and .9195 for gender effect (see Tables F-37 and F-38). Graphic illustration of the data in Table F-37 depicts the left-right variations observed for each stage presented as actual measure (cm) and as a percent of standing height (Figure 44). Greater (28%, 33% standing height) linear displacements of the centers of mass of the left arm

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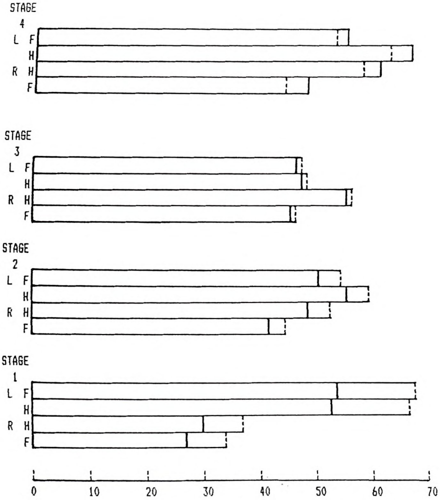

Key: (|) = actual displacement, (¦) = percent of standing height.
L = left, R = right, H = humerus, F = forearm.

Figure 44. Linear displacement (cm and percent of standing height) of centers of mass for humerus and forearm from humerus maximum forward position to humerus maximum backward position.

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segments were particularly prominent in stage one. Stage two and four subjects also had greater (5% to 10% standing height) linear displacements of the centers of mass of the left arm segments whereas stage three subjects had greater (9% standing height) displacement of the center of mass of the right humerus. Males displayed greater (1% to 4% standing height) linear displacements of the centers of mass of right and left humerus segments than females. Linear displacements of the centers of mass for the left limb were greater (6% to 16% standing height) than those for the right limb for both boys and girls (see Table F-38).

Angular Displacement of Arm Segments. Angular displacements of the humerus and forearm were evaluated from maximum forward position of the humerus to its maximum backward position, measured from the distal end of the segment, counterclockwise relative to the horizontal (see Figure 21, p. 90). Analysis of the data yielded p values of .0528 and .8698 for stage effect and .4476 and .6824 for gender effect (see Tables F-39 and F-40). Follow up tests revealed significant differences (p.0023) for angular displacement of the right forearm. Stage one differed from stages two, three, and four. Stages two and three differed from stages one and four. Stage four differed from stages one, two, and three. The right-left differences observed in the angular displacements of the centers of mass of the arm segments were even more striking than in their linear displacements (see Figure 45). In stage one, there was very little (-3.02°) difference in the left-right angular displacements of the humeri, but considerable (-40.74°) difference in the forearms.

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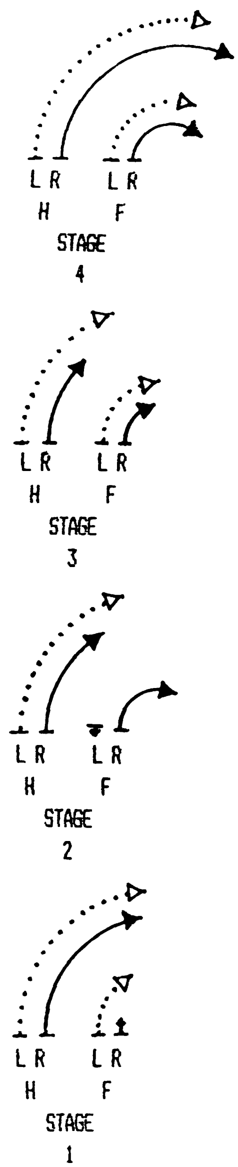

Key: H = humerus, F = forearm, L = left, R = right. Arrow indicates direction of displacement.

Note: Significance in right forearm. 1 2 3 4

Figure 45. Angular displacement (deg) of humerus and forearm from humerus maximum forward position to humerus maximum backward position.

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Stage two presents a mixture. The right forearm had greater (-45.07°) angular displacement than the right humerus, but the left humerus had greater (-71.05°) angular displacement than the left forearm. In stage three, the left humerus had greater (-17.58°) angular displacement than the right humerus, but the forearm angular displacements were almost (0.59°) the same. In stage four, angular displacement was greater in the right humerus (-14.77°) and forearm (-33.05°) than in the left. Females had greater (-1.0°, -12.74°) humeri angular displacements than males, but males had greater (-10.01°, -16.22°) forearms angular displacements than females (Table F-40). Males had greater (-.081°, -20.51°) angular displacement in the right humerus and forearm than in the left whereas the females presented a mixture of results. For future research efforts, it might be interesting to attempt to assess the hand dominance of the subjects to determine if there is any relationship with the magnitudes of the angular and linear displacements of centers of mass of arm segments.

Summary of Results

This experimental interdisciplinary study used biomechanics research techniques to investigate the motor development stages (rather than age or grade common to previous research) for running in young children. Kinematic variables selected for investigation represented the distinguishing characteristics of the developmental stages of running according to Seefeldt et al. (1972). The variables investigated were grouped into seven major categories: (a) running descriptors;

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(b) segmental inclinations; (c) distance between the downward vertical projection of the body's center of gravity and the foot at touchdown; (d) sequence of peak angular velocity for leg segments; (e) midline-limb segment center of gravity distance; (f) temporal analysis; and (g) limb segment displacements. Statistical significance ($p \leq .05$) was obtained for stage effect for mean trochanteric height, running speed, right shank at touchdown, right forearm at humerus maximum backward position, angular displacement of right forearm, and for gender effect in the left shank at maximum leg extension. Since analysis of gender by stage groups could not be done due to the small number of subjects in the study, comment on the degree of any found or possible gender differences must wait for further research. However, of more notable importance were the developmental trends across the stages that were identified in almost all the areas of inquiry.

By investigating action on both sides of the body (as opposed to single side analysis common among previous research) and then attempting to consolidate the multitude of variables analyzed, one gains intriguing insight into the intricacies underlying the qualitative characteristics previously identified for the developmental stages of running. Although symmetrical performance was not expected, diverse right-left variations were consistently observed among the data for stage two and stage three runners. Here again one must be somewhat cautious in that right-left differences range from less than one to as much as 10-20+ degrees, centimeters or percent of standing height.

The data revealed two general patterns. These were left to right and thigh to shank relationship across stages and events. For example

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in comparing right and left touchdown across stages, the leg with the combination of lower thigh segment inclination and higher shank segment inclination (see Table F-1) made contact with the supporting surface farther (1-8% of standing height) ahead of the downward vertical projection of the body's center of gravity (see Table F-15). The opposite combination (higher thigh segment inclination, lower shank segment) made contact closer (1-8% standing height) to the downward vertical projection of the body's center of gravity. This combination held true across the stages and between gender groups. In the stage four runners the left leg made contact farther ahead (3% standing height) of the downward vertical projection of the body's center of gravity than the right leg. This left-right, thigh-shank relationship was observed across events (touchdown, maximum leg extension, takeoff, minimum knee angle and maximum thigh segment height) for stage four runners. This same relationship was observed in stage two and three runners for touchdown, maximum leg extension, and takeoff and in stage one runners at touchdown, takeoff and maximum thigh segment height.

A second right to left and thigh to shank relationship observed in stages one through three was that of the higher thigh to shank inclinations occurring in the same leg. This relationship was observed at maximum leg extension for stage one runners, minimum knee angle for stage one through three runners and at maximum thigh segment height for stage two and three runners.

Evidence of the proximodistal development (Espenschade and Eckert, 1980, Haywood, 1986) is seen in the qualitative differences of limb action, but can be lost in the segmental approach to quantitative analyses. The investigation of arm action in the present study was an example of this. Qualitatively there is considerable difference in what is happening in whole arm action (see Figures 8-11, pp 46-49), yet when segmentally measured from the sagittal plane (side view) the qualitative differences are much less evident. Expanding the way in which arm action is investigated, beyond the drawn midline-limb segment center of gravity distance measures attempted in the present study, would help more accurately quantify the observed qualitative differences in arm action.

The developmental stages characterize differences in mechanical efficiency in the developing skill. The differing quantitative measures lend evidence to the identified qualitative differences across the stages. Yet the similarities in time and percent of support-nonsupport and magnitudes of obtained measures in linear (actual measurement in centimeters and percent of standing height) and angular (degrees and radians) displacements across stages give evidence of invariances within the developing skill. The degree of relationship among leg and arm measures of inclinations, displacements, and sequence of peak velocities (both linear and angular) for the developing runner as opposed to the mature, adult runner, awaits further research. Inclusion of these variables in future research may help increase understanding of the relationship of neurophysiological maturation and sequential summation of the power train in motor skill development.

Reflections on the Analyses Process.

The traditional $p<.05$ level of significance was adhered to in this study. This researcher now questions the appropriateness of $p<.05$ to identify statistical significance in future research of this type. This belief is based on five factors:

1. the limited number of subjects,
2. the accepted qualitative differences in running form used across the stages,
3. the developmental trends disclosed among the various individual quantitative measures,
4. the number of obtained p values between .05 and .20, and
5. the several places where p values of less than .05 occurred yet the location of statistical difference(s) could not be identified through follow up testing.

Strictly adhering to the $p<.05$ level may be too stringent to flush out what is believed to be hidden significance, in the statistical sense, when research techniques and restrictions demand the use of a small number of subjects. In the present study evidence (as described above) of something happening (or about to happen) can be found in as many as 15 different stage effects and 11 different gender effects. (Again the reader is cautioned in respect to the potential of gender effects since stage by gender analyses were not possible in the present study.) In addition, since the identified qualitative characteristics distinguish points along a continuum of immature to mature skill form and since biomechanical research techniques are more likely to distinguish

extremes rather than gradations in performance (Ulibarri, personal communication, October 26, 1987), the suggestion that future researchers to consider a less stringent level of significance is strengthened, if indeed one desires to identify statistical differences in performance. For the present study, the types of information about the developmental stages and the obtained quantitative evidence to support the observed qualitative trends is of far greater importance to the understanding of skill development than whether a variable was statistically significant.

Chapter V

Conclusion and Recommendations

This chapter contains two main sections. Concluding remarks and new questions arising from the present research will be presented in the first section. The second section will contain a series of recommendations for future research into the development of running skill in young children.

Conclusion

Previous research by physical educators specializing in motor development and developmental biomechanics has contributed greatly to the understanding of the development of fundamental motor skills, running particularly, in young children. The developmental biomechanics research has provided kinematic and kinetic information on position and movement of body segments and joints during skill performances by children of differing age or grade and gender (e.g. Fortney, 1980, Mersereau, 1977). The motor development research into developmental staging of motor skills has identified age related, but not age dependent, changes for key descriptive characteristics in developing fundamental motor skills in young children (e.g. Seefeldt et al, 1972).

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These key descriptive characteristics in developing skills are generally synonymous to kinematic variables investigated by age or grade level in developmental biomechanics studies. Prior to the present study, biomechanical analysis of the identified developmental stages of various fundamental motor skills, as defined, had not been attempted. The present interdisciplinary study was therefore undertaken to explore the potential for using biomechanical research techniques, specifically high speed cinematography, to help determine the extent and significance of mechanical differences observed in developing running skill. Selected kinematic and anthropometric variables for the skill of running were investigated to define which specific variables, if any, differed among the four developmental stages as well as between the performance of boys and girls. Considering the research techniques used and previous research in developmental staging of motor skills, a very small number of subjects was selected for the present study with the understanding of the risks involved both from the standpoint of statistical analysis and the unpredictability of preschool age children.

The variables investigated in the present study were categorized into seven major areas: (a) running descriptors (stride length, stride rate, stride time, cycle length, total right-left cycle distance, total right-left cycle time, running speed, and selected anthropometric measures as they relate to running skill); (b) segmental inclinations at selected points during the running cycle; (c) distance between the downward vertical projection of the body's center of gravity and the foot at touchdown; (d) sequence of peak angular velocity for leg segments; (e) drawn midline-limb segment center of gravity distance at

selected points during the running cycle; (f) temporal analysis; and (g) limb segment displacements, both linear and angular. The variables were analyzed for each leg in order to observe differences between right and left limb actions.

Two hypotheses were examined in this study: (a) each of the selected kinematic variables will follow the predicted trends, showing significant differences from stage to stage, in the running behavior of young children, and (b) there will be no statistical differences for each of the selected kinematic variables across stages between boys and girls. The results of this study fail to support the first hypothesis. Only five variables yielded statistical significance for stage effect, (trochanteric height, running speed, right shank at touchdown, right forearm at maximum humerus backward position, and angular displacement of the right forearm). Whether the lack of statistical significance for the other variables was due to the small number of subjects studied or to actual nonsignificance among the variables as they were measured can only be determined by further research using much larger numbers of subjects. However, many of the predicted trends were followed, developmental trends were present, and of the variables investigated, several items provided valuable insight into running skill development.

The second hypothesis, that there will be no statistical differences between boys and girls across stages on each of the selected kinematic variables was not fully supported by the results of this study because a significant difference was indicated for the left shank at maximum leg extension. However, the reader is cautioned. The small number of subjects made it impossible to cross analyze variables by

gender by stage. Before one can verify that no differences exists between gender groupss or among the stages additional research needs to be conducted with enough subjects to warrent stage by gender statistical analysis.

The use of high speed cinematography not only allows the researcher to review, repeatedly, the skill performance of a child, it also reveals elements of the skill that are otherwise unobservable to the naked eye. No flight was observed in the skill performance of the stage one female until the film was first reviewed. The .04 seconds of flight present in her run immediately raised the question of how long must flight be before it is visible to the naked eye? A first hint as to the arrhythmical run often observed in stage two and three runners was also revealed through analysis of the film. Occasionally a child would not have flight on one side of the body. This observation raises the question at what point does the rhythmical quality of the run even out?

Of particular note and interest were the consistently larger left-right limb variations among the variables studied in the stage two and stage three runners. The right-left variations were first revealed in the segmental inclinations data giving indication of a reason for the choppy run often observed in the children running in stage two and stage three. A further basis for this arrhythmical run became particularly apparent from the temporal analysis and linear and angular displacement data analysis. The larger right-left variations in stages two and three were also evident in the data analyzed from the frontal film (front view). Graphic illustrations (Figures 36 and 37, pp. 147-148) of the distance between the midline and limb segments centers of gravity

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provided an interesting view of the development of the counterrotary reaction at the selected events during the running cycles for each leg. The researcher cannot help but wonder that if the drawn midline-limb segments' center of gravity information were combined with linear and angular displacement data for both arms and legs, would it provide greater insight to the development of running skill in young children?

Little research on the development of arm action in running has been attempted in the past. The present study investigated arm segment inclinations at maximum forward and maximum backward humeri positions as well as the linear and angular displacements between these two positions. In retrospect, and in light of the type of information obtained, the researcher believes it would have been more informative to analyze arm inclinations at the same positions leg inclinations were investigated. Likewise, analysis of arm linear and angular displacements during the same periods used for the angular and linear displacements of the leg segments analysis might have proven more informative. Then comparisons, similar to the one done for limb segments' center of gravity from the drawn midline could have been made. The observation of the results of the distance limb segments' center of gravity distance from the midline raised the question of when during the development of running skill does arm motion become less of a reaction to and more of a contribution to running? Although the data analyzed in the present study provided insight into the development of arm action, the researcher questions if there might be some other, more informative method of studying developing arm action in running?

Both linear and angular displacement data were generated by

the biomechanics software program used by this researcher, each were analyzed for the subjects to determine which data might be more useful to motor development skill study. The linear and angular data analyses for the subjects studied provided fascinating insight into the development of the running skill. Which displacement data would prove more useful to motor development will depend on what any one researcher is attempting to interpret. If the ultimate goal of this type of research is to help the preschool and elementary physical education teacher better understand and observe skill development and to plan more effective programs, then perhaps the angular displacement information might be more easily observed and interpreted by the teacher in the school gymnasium (especially for individuals with a limited background in physics and biomechanics).

The timing and film observation of action from maximum leg extension to takeoff in the stage one and stage two runners studied raised some questions. Maximum leg extension occurred prior to takeoff in stages one and two. These runners seemed to achieve the maximum leg extension then ride their momentum onto the opposite leg or into flight. This observation raised the question of where does the actual extension of the leg segments during the drive interval cease in relation to takeoff? How do the amount and timing of extension and summation of power train relate to neurological development of the young runner? A kinetic analysis of the developmental stages of running would begin to provide insight into this observation?

The research of Fortney (1980) and Mersereau (1974) provided much stimulation for this researcher's present effort. Among the variables

Mersereau (1974) investigated with her 22- and 25-month-old girls was the distance between the downward vertical projection of the body center of gravity and support foot at touchdown. Since Mersereau's (1974) results (an increase in the distance from 22 months to 25 months in age) were opposite of those obtained by Dittmer (1965) (a decrease in distance as age increased from five to eleven years), this variable was included in the present study in an attempt to obtain a possible understanding of the conflicting results in the two previous studies. The findings of the present study suggest that the Mersereau (1974) and Dittmer (1965) results were not contrary, but at opposite ends of a developmental trend. In the present study the distance increased from stage one to stage two, then progressively decreased from stage two to stage four. Further research on this variable is needed to verify this developmental trend.

A study of running skill development by age (2-, 4-, and 6-year olds) conducted by Fortney (1980), resulted in significant differences between the 2-year olds and the 4- and 6-year olds, but no differences between the 4- and 6-year-olds. Fortney (1980, personal communications, February 14, 1985 and April 14, 1987) raised the question of what might be happening to the running performance of 3-year-olds. Considering that developmental stages are age related, but not age dependent; that the mean age for stage two, stage three, and stage four runners are 2.5, 3.5, and 4.0-4.5 years, respectively (Early Childhood, 1985); and the comparison running indices by age and stage in Table 12 (p. 106) are similar, one might suggest that indeed something was happening in the running skill of 3-year-olds. More research by

developmental stage, involving greater numbers of subjects is needed to answer the question raised by Fortney (1980, personal communications, February 14, 1985 and April 14, 1987) and to verify the findings of the present study.

Despite the lack of statistical significance for stage effect, the researcher feels the present study did, indeed, reveal that the use of biomechanical research techniques to investigate the developmental stages of running will provide invaluable information and insight into skill development in young children. This motor development researcher echoes Garrett's (1978) expression of the promise of synergistic research efforts between motor development and developmental biomechanics specialists.

Recommendations

Based on the experience gained and the results obtained from conducting the present study, the following recommendations are made:

1. If additional research is conducted on the developmental stages of running skill, it should be a cooperative, team effort involving at the least individuals specializing in developmental biomechanics and motor development. Individuals interested in motor learning, developmental psychology, developmental neurology, and developmental neurophysiology would also be valuable additions to a team approach to a study of running skill development.
2. A future study in skill development should contain enough subjects to permit statistically cross comparisons of limb side, gender, stage,

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and age to obtain a more detailed understanding of skill development. Such cross comparisons would provide deeper insight into the developing skill. Perhaps more important, such comparisons may provide greater understanding of age versus stage changes in motor skill development.

3. Once the minimum number of subjects is ascertained to conduct the desired statistical analyses, select and film twice as many subjects, if possible. Preschool children are unpredictable in their behavior. Some may perform at, or above, expected skill stage and others may perform poorly when placed in the formal situation of data collection. Also, it is unknown when a child may move into transition between stages. Since one day may make a difference, longitudinal study of skill development in young children would be valuable. If extra subjects are filmed, the best possible representations of each developmental stage could be obtained in the quantities needed for statistical analysis.

4. Future studies should consider adding kinetic variables to the data analysis to obtain developmental information on these factors. The collection of data that requires technical equipment to be applied to the subject's body or to be crossed by the subject creates additional challenges in dealing with preschool age children. However, the potential of kinetic data for increasing the understanding of skill development would be well worth the effort if the expertise, equipment, and computer programming are available.

5. Future studies should investigate the path of the body's center of gravity. Both horizontal and lateral oscillations should be investigated to determine differences among the developmental stages. One might also note the location of the body's center of gravity within

the runners performing at each stage and what effect this location (or the movement of) might have on the developing skill performance.

6. Future studies should investigate arm segment inclinations, velocities, and displacements at the same points and periods as leg segments to obtain a more detailed understanding of the total skill development. Likewise, investigate both right and left limbs to gain better understanding of developmental stage differences.

7. Future research should attempt to determine the subjects' ability to maintain states of static balance and dynamic control for right and left limbs to correlate with skill development data in an effort to determine to what degree, if significant relationships are evident between balance development and motor skill development.

8. Future research in motor skill development should continue to use multidimensional analysis using whatever state-of-the-art systems are available to the research team (e.g. Cellspot, Watsmark, optoelectric). Consideration should also be given to overhead and/or three dimensional analysis if such equipment and computer programming is available to the research team.

9. If at all possible, at least one member of the research team should be familiar with the subjects prior to the data collection. This researcher made an effort to visit the classes attended by the subjects and became familiar with the motor skill patterns used by the children in informal play situations. Although most of the children were familiar with the testing situation as conducted in the Early Childhood (1985) research, the filming situation was new. The more at ease the children are with the researcher(s) and the surroundings the

more likely they are to perform in their true developmental stage. Researchers not intending to collect force platform generated data might consider collecting data in a gymnasium more familiar to the children than the formality of a human performance laboratory (assuming proper lighting conditions are available for the system used for data gatherings). Consideration might also be given to the time of day the child is to be filmed in order to obtain the child's truest developmental stage performance.

APPENDICIES

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APPENDIX A

Early Childhood Motor Skills Development Study Tables on Running

Table

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GENDER (N)
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Table A-1

Percent of Children Running at Various Stages by Age and Gender.

AGE IN MONTHS

(Age in Years)

	30-35 (2.5)		36-41 (3.0)		42-47 (3.5)		48-53 (4.0)		54-59 (4.5)		60-65 (5.0)		MALE TOTALS		FEMALE TOTALS	
													(%)	(N)	(%)	(N)
GENDER (N)	M (134)	F (124)	M (175)	F (166)	M (199)	F (125)	M (159)	F (118)	M (123)	F (68)	M (69)	F (34)	(100)	(859)	(100)	(635)
STAGE 4	3.7	0.8	13.1	2.4	28.6	8.0	37.1	22.0	59.3	38.2	60.9 (a-)	52.9	30.2	259	13.4	85
STAGE 3	39.6	34.7	54.3- (a-)	52.4	51.8 (a)	71.2- (a-)	48.4 (a)	63.6 (a)	32.5 (a+)	48.4 (a)	29.0+	41.2+ (a+)	45.2	388	53.7	341
STAGE 2	56.0+ (a+)	58.9 (a)	31.4	43.4+ (a+)	19.6	20.8	14.5	14.4	8.1	13.2	10.1	5.9	24.3	209	31.3	199
STAGE 1	0.7	5.6	1.1	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	3	1.6	10
PRE-STAGE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0
S. D.	0.6	0.6	0.7	0.6	0.7	0.5	0.7	0.6	0.6	0.7	0.7	0.6				

a = The median stage for each age group. + or - indicates transition between stages. For example a+ indicates the median stage for 4.5 year old males is 3+.

underlined numbers = The mean stage for that particular age. + or - indicate transition between stages. For example 43.4+ indicates three year old females mean stage is 2+.

Note: From The Early Childhood Motor Skills Development Study (1985). Standards of Performance on Selected Fundamental Motor Skills for Preschool Age Children. Tabulated data. School of Health Education, Counseling Psychology, and Human Performance, Michigan State University, East Lansing, Michigan.

Table

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Table A-2

Percentile Ranks with Transitions Separated from Whole Stage Running Performance by Age and Gender.

AGE/ GENDER		(N)	1-	1	1+/2-	2	2+/3-	3	3+/4-	4	MEDIAN	S. D.
2.5	M	(134)		1	1	40	70	92	98	100	2+	1.1
	F	(124)		2	11	47	77	94	99	100	2+	1.1
3.0	M	(175)		1	3	21	45	80	93	100	2+/3-	1.2
	F	(166)		1	3	34	55	93	99	100	2+	1.1
3.5	M	(199)				12	26	61	81	100	3	1.2
	F	(125)			1	14	32	79	97	100	3-	1.0
4.0	M	(159)				9	21	53	79	100	3	1.2
	F	(118)			1	11	23	67	83	100	3	1.2
4.5	M	(123)				5	10	31	54	100	3+	1.1
	F	(68)				9	16	50	79	100	3	1.2
5.0	M	(69)				3	10	33	61	100	3+	1.1
	F	(34)				6	9	29	68	10	3+/4-	1.1

Note: From The Early Childhood Motor Skills Development Study (1985). Standards of Performance on Selected Fundamental Motor Skills for Preschool Age Children. Tabulated data. School of Health Education, Counseling Psychology, and Human Performance, Michigan State University, East Lansing, Michigan.

Table A-3

Mean 15-Ya

Gender.

AGE	GEND
2.5	M
	F
3.0	M
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Table A-3

Mean 15-Yard (13.71 Meter) Run Times in Seconds and Speeds by Age and Gender.

AGE	GENDER	N	$\bar{X}$ TIME	S. D.	RANGE	YARDS/SECOND	METERS/SECOND
2.5	M	107	5.71	1.30	8.67	2.63	2.40
	F	98	5.56	1.18	7.79	2.70	2.46
3.0	M	140	4.93	1.08	8.23	3.04	2.78
	F	134	5.15	1.03	6.81	2.91	2.66
3.5	M	165	4.41	0.78	5.01	3.40	3.11
	F	98	4.59	0.74	4.31	3.27	2.99
4.0	M	124	4.12	0.64	3.93	3.64	3.33
	F	98	4.32	0.73	4.12	3.47	3.17
4.5	M	97	3.90	0.48	2.84	3.85	3.51
	F	52	3.93	0.54	2.91	3.82	3.49
5.0	M	54	3.71	0.47	2.03	4.04	3.69
	F	25	3.73	0.31	1.25	4.02	3.67

Note: From The Early Childhood Motor Skills Development Study (1985). Standards of Performance on Selected Fundamental Motor Skills for Preschool Age Children. Tabulated data. School of Health Education, Counseling Psychology, and Human Performance. Michigan State University, East Lansing, Michigan.

Table A-

Mean 30-
Gender.

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Table A-4

Mean 30-Yard (27.42 Meter) Run Times in Seconds and Speeds by Age and Gender.

AGE	GENDER	N	$\bar{X}$ TIME	S. D.	RANGE	YARDS/SECOND	METERS/SECOND
2.5	M	107	11.86	2.71	17.37	2.53	2.31
	F	99	11.63	2.48	15.63	2.58	2.36
3.0	M	138	10.23	2.55	20.75	2.93	2.68
	F	134	10.61	2.04	11.67	2.83	2.58
3.5	M	165	8.99	1.63	12.71	3.34	3.05
	F	98	9.35	1.48	7.08	3.21	2.93
4.0	M	124	8.35	1.38	9.51	3.59	3.28
	F	98	8.63	1.45	8.22	3.48	3.17
4.5	M	97	7.83	1.06	6.59	3.83	3.50
	F	52	7.90	1.09	5.83	3.80	3.47
5.0	M	54	7.37	1.01	5.12	4.07	3.72
	F	25	7.38	0.61	2.82	4.06	3.71

Note: From The Early Childhood Motor Skills Development Study (1985). Standards of Performance on Selected Fundamental Motor Skills for Preschool Age Children. Tabulated data. School of Health Education, Counseling Psychology, and Human Performance, Michigan State University, East Lansing, Michigan.

Table A-5

Percentile Ranks

and Gender.

AGE/ GENDER		(N)	10
5.0	M	54	8.64
	F	25	7.70
4.5	M	97	9.09
	F	52	9.50
4.0	M	124	9.50
	F	98	10.40
3.5	M	165	11.00
	F	98	11.42
3.0	M	138	12.17
	F	134	13.60
2.5	M	107	14.70
	F	99	14.44

Note: From The Ea

Standards of Perfo

Preschool Age Chil

Counseling Psychol

East Lansing, Mich

Table A-5

Percentile Ranks for 30-Yard (27.43 Meter) Run Times in Seconds by Age and Gender.

AGE/ GENDER		(N)	10	20	25	40	50	60	70	80	90	100	Med.	S.D.
5.0	M	54	8.64	7.70	7.65	7.45	7.31	7.02	6.79	6.66	6.48	5.88	7.30	1.01
	F	25	7.70	7.81	7.80	7.64	7.43	7.29	7.07	6.90	6.77	5.87	7.40	0.61
4.5	M	97	9.09	8.48	8.27	7.99	7.77	7.56	7.32	6.95	6.68	6.06	7.71	1.06
	F	52	9.50	8.75	8.55	7.98	7.76	7.62	7.34	7.07	6.71	6.07	7.75	1.09
4.0	M	124	9.50	9.04	8.84	8.39	8.14	7.97	7.73	7.51	7.05	6.20	8.13	1.38
	F	98	10.40	9.56	9.29	8.70	8.51	8.17	7.97	7.66	7.07	6.33	8.49	1.45
3.5	M	165	11.00	10.10	9.86	9.26	8.94	8.46	8.03	7.60	7.24	5.85	8.91	1.63
	F	98	11.42	10.56	10.25	9.59	9.14	8.60	8.35	8.15	7.85	6.80	9.12	1.48
3.0	M	138	12.17	11.18	10.96	10.02	9.76	9.40	9.09	8.84	8.20	6.31	9.73	2.55
	F	134	13.60	11.90	11.19	10.49	10.25	9.90	9.62	9.23	8.60	7.54	10.20	2.04
2.5	M	107	14.70	13.42	13.17	11.98	11.47	10.96	10.39	9.94	9.01	6.82	11.43	2.71
	F	99	14.44	12.80	12.50	11.96	11.51	10.80	10.28	9.92	8.90	7.13	11.46	2.48

Note: From The Early Childhood Motor Skills Development Study (1985). Standards of Performance on Selected Fundamental Motor Skills for Preschool Age Children. Tabulated data. School of Health Education, Counseling Psychology, and Human Performance, Michigan State University, East Lansing, Michigan.

Table A-6

30-Yard Run Tim

STAGE	AGE
4	5.0
	4.5
	4.0
	3.5
	3.0
	2.5
3	5.0
	4.5
	4.0
	3.5
	3.0
	2.5

Continued on next page

Table A-6

30-Yard Run Times in Seconds and Speeds by Stage, Age, and Gender.

STAGE	AGE	GENDER	N	$\bar{X}$	MEDIAN	RANGE	S.D.	YDS/SEC	M/SEC
4	5.0	M	33	7.04	7.00	2.85	0.64	4.26	3.89
		F	14	7.17	7.13	2.82	0.65	4.18	3.82
	4.5	M	57	7.57	7.58	3.92	0.92	3.96	3.62
		F	21	7.39	7.10	3.59	0.95	4.06	3.71
	4.0	M	48	7.84	7.82	3.27	0.79	3.83	3.50
		F	23	7.54	7.64	3.14	0.88	3.98	3.64
	3.5	M	52	8.28	7.97	5.95	1.31	3.62	3.31
		F	9	8.75	8.15	3.00	1.05	3.43	3.13
	3.0	M	20	8.67	8.81	4.49	1.20	3.46	3.16
		F	4	9.47	9.90	2.48	1.13	3.17	2.89
	2.5	M	5	9.25	8.70	6.24	2.34	3.24	2.96
		F	1	8.50	8.50	-	-	3.53	3.23
3	5.0	M	16	7.55	7.36	3.79	0.89	3.97	3.63
		F	10	7.23	7.66	1.57	0.49	4.15	3.79
	4.5	M	32	7.99	7.91	4.48	0.89	3.75	3.43
		F	26	8.01	7.91	2.64	0.76	3.74	3.42
	4.0	M	58	8.31	8.18	5.56	1.02	3.61	3.30
		F	60	8.69	8.56	5.04	1.10	3.45	3.15
	3.5	M	83	9.10	9.03	6.75	1.39	3.30	3.01
		F	71	9.06	8.98	5.03	1.18	3.31	3.03
	3.0	M	71	10.02	9.64	19.62	2.39	2.99	2.74
		F	74	9.77	9.69	5.50	1.21	3.07	2.81
	2.5	M	42	11.11	10.76	8.80	1.99	2.70	2.47
		F	33	11.13	10.53	11.72	2.34	2.69	2.46

Continued on next page.

Table A-6 Continued

STAGE	AGE	GEN
2	5.0	M
		F
	4.5	M
		F
	4.0	M
		F
	3.5	M
		F
	3.0	M
		F
	2.5	M
		F
1	5.0	M
		F
	4.5	M
		F
	4.0	M
		F
	3.5	M
		F
	3.0	M
		F
	2.5	M
		F

Note: From The Earl
Standards for Perfor
Preschool Age Childr
Counseling Psycholog
University, East Lan

Table A-6 Continued.

STAGE	AGE	GENDER	N	$\bar{X}$	MEDIAN	RANGE	S.D.	YDS/SEC	M/SEC
2	5.0	M	2	9.00	8.64	4.09	1.69	3.33	3.05
		F	1	7.78	8.64	-	-	3.86	3.52
	4.5	M	7	9.24	8.82	5.09	1.67	3.25	2.97
		F	5	9.47	9.05	4.03	1.53	3.17	2.89
	4.0	M	17	9.97	9.00	7.16	2.33	3.01	2.75
		F	15	10.09	9.33	6.18	2.00	2.97	2.72
	3.5	M	30	9.92	9.57	11.67	2.18	3.02	2.76
		F	17	10.81	10.56	5.73	1.93	2.77	2.54
	3.0	M	45	11.03	10.41	14.60	2.78	2.72	2.48
		F	50	11.51	10.64	9.88	2.13	2.16	2.38
	2.5	M	59	12.62	12.00	15.63	2.94	2.38	2.17
		F	60	11.73	11.70	15.63	2.38	2.56	2.34
1	5.0	M	0	-	-	-	-	-	-
		F	0	-	-	-	-	-	-
	4.5	M	0	-	-	-	-	-	-
		F	0	-	-	-	-	-	-
	4.0	M	0	-	-	-	-	-	-
		F	0	-	-	-	-	-	-
	3.5	M	0	-	-	-	-	-	-
		F	0	-	-	-	-	-	-
	3.0	M	2	14.67	14.67	3.12	2.21	2.04	1.87
		F	3	16.28	15.54	5.11	2.63	1.84	1.68
	2.5	M	1	10.96	10.96	-	-	2.74	2.50
		F	5	14.32	14.10	6.64	3.04	2.09	1.91

Note: From The Early Childhood Motor Skills Development Study (1985). Standards for Performance on Selected Fundamental Motor Skills for Preschool Age Children. Tabulated data. School of Health Education, Counseling Psychology, and Human Performance, Michigan State University, East Lansing, Michigan.

APPENDIX B

Parental Information

MICHIGAN STATE UN

COLLEGE OF EDUCATION • SCHOOL OF
COUNSELING PSYCHOLOGY AND HUMA
SPORTS CIRCLE

Dear Parent,

Recently I spoke w
my dissertation re
age boys and girls
study as well as t

The purpose of the
stages identified
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running down a sho
view) may be reque
from your child.
measurements will
arm and leg joints
shorts/swim suits
for the Study of H
Michigan State Uni

Measurement and fi
understanding of t
also is the potent
students and educa
only be after you
and have given you
identified only by
results will be tr
anonymous.

Upon your arrival
be asked to comple
studies using huma
required before yo
you on April 30 or

If you change your
have any questions
355-9931).

Thank you very muc

Sincerely,

Joy E. Kiger
Project Coordinato
Graduate Teaching/
Assistant, Motor D

Your Scheduled Fil

MICHIGAN STATE UNIVERSITY

COLLEGE OF EDUCATION • SCHOOL OF HEALTH EDUCATION
COUNSELING PSYCHOLOGY AND HUMAN PERFORMANCE •
IM SPORTS CIRCLE

EAST LANSING • MICHIGAN • 48824-1049

Dear Parent,

Recently I spoke with you concerning an interest in including your child in my dissertation research study on the development of running in preschool age boys and girls. This letter is to inform you of the details of the study as well as the extent of your involvement.

The purpose of the study is to do a kinematic analysis of each of the four stages identified in the development of running skill. This will be done by simultaneous, high-speed filming of side and front views of children running down a short runway. Your assistance, (out of camera field of view) may be requested in order to elicit the best possible performance from your child. Prior to the filming, a set of anthropometric measurements will be taken and small stick-on markers will be placed on all arm and leg joints. Children will need to be dressed only in diapers or shorts/swim suits and sneakers. All filming will take place in the Center for the Study of Human Performance (Erickson Hall) on the campus of Michigan State University.

Measurement and film data collected will be used to further the understanding of the development of running skill in young children. There also is the potential for using the film to assist in the education of students and educators in running skill development. However this would only be after you have had the opportunity to review the film of your child and have given your written consent. The children in the film will be identified only by subject number and birth date. All calculated data results will be treated with strict confidence and subjects will remain anonymous.

Upon your arrival at the Center for the Study of Human Performance you will be asked to complete consent forms according to university regulations for studies using human subjects. Parent signature on the consent forms is required before your child may participate in the study. I will be calling you on April 30 or May 1 to remind you of the filming time you selected.

If you change your mind on your child's participation in this project or have any questions, please call me (office: 353-9459 or 353-3866; home: 355-9931).

Thank you very much for your time and effort.

Sincerely,

Joy E. Kiger
Project Coordinator and
Graduate Teaching/Research
Assistant, Motor Development

Your Scheduled Filming Time: ______________________________

MICHIGAN STATE UNIV

COLLEGE OF EDUCATION • SCHOOL OF H
COUNSELING PSYCHOLOGY AND HUMAN
SPORTS CIRCLE

The purpose and
to my satisfaction.
and am willing to a
the risks involved
without recriminati

I understand tha
(and/or my child's)
University will pro
any other medical e
program.

I understand the
with strict confide
to view the films o
such films may be u

Child's Name: ____________

Parent's Signature:

Date: ____________

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Motor Development Dissertation Study

Consent Form

The purpose and extent of involvement in this project has been explained to my satisfaction. I agree to my child's participation in this project and am willing to assist in eliciting responses if necessary. I understand the risks involved and am free to discontinue participation at any time without recrimination.

I understand that if I [and/or my child] am injured as a result of my [and/or my child's] participation in this research project, Michigan State University will provide emergency medical care if necessary, but these and any other medical expenses must be paid from my own health insurance program.

I understand the results of my child's participation will be treated with strict confidence. I also understand that I will have an opportunity to view the films of my child and must give my written permission before such films may be used for ecucational or other purposes.

Child's Name: ______________________________

Parent's Signature: ______________________________

Date: ____________________

[MI]CHIGAN STATE UNI[V...]

[COLL]EGE OF EDUCATION • SCHOOL OF [...]
[COUNSEL]ING PSYCHOLOGY AND HUMAN [...]
[...]RTS CIRCLE

Subject Name___

___ I/we have cho[...]
of my/our chi[...]
the project d[...]
purposes.

Parent/Guardian ___

___ I/we have vie[...]
child.

___ All of the fi[...]
director and/[...]

___ Only sections[...]
be used by th[...]
educational p[...]

Parent/Guardian___

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COUNSELING PSYCHOLOGY AND HUMAN PERFORMANCE •
IM SPORTS CIRCLE

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Running Development Study

Film Release Form

Subject Name ______________________ Subject # ______________________

_____ I/we have chosen not to view the Running Development Study film made of my/our child and give my/our permission for the film to be used by the project director and/or Michigan State University for educational purposes.

Parent/Guardian ______________________ Date ______________

_____ I/we have viewed the Running Development Study film made of my/our child.

_____ All of the film made of my/our child may be used by the project director and/or Michigan State University for educational purposes.

_____ Only sections designated below from the film made of my/our child may be used by the project director and/or Michigan State University for educational purposes.

Parent/Guardian ______________________ Date ______________

A

APPENDIX C

Anthropometric Measurement Procedures

A

The followin

are described for

those outlined by

are recorded to t

Note: To ob

young subjects it

the child assist i

will be noted in s

study measurements

body. Several of

taken on the left

Anthropometric Measurements Procedures

The following written descriptions of anthropometric measurements are described for the right side of the body. These procedures follow those outlined by Seefeldt, Haubenstricker, Brown, and Branta (1983) and are recorded to the nearest millimeter.

Note: To obtain the most accurate measurement possible on very young subjects it is often necessary to have another person familiar to the child assist in positioning various body segments. Such assistance will be noted in several of the following illustrations. For this study measurements were made on both the right and left side of the body. Several of the pictures will illustrate the measurement being taken on the left side of the body.

Measurements Usinc

Shoulder Width (Bi

The subjects stanc

with their back tc

taking the measure

their shoulders "c

The acromion proce

pated using the ir

One end of the cal

on the lateral edg

acromion and the c

until it was in pl

lateral edge of th

acromion.

Measurements Using the Bow Caliper

Shoulder Width (Biacromial Diameter). The subjects stand on both feet with their back to the person taking the measurements and let their shoulders "droop down." The acromion processes are palpated using the index fingers. One end of the caliper is placed on the lateral edge of one acromion and the other end moved until it was in place on the lateral edge of the other acromion.

Hip Width (Biil

With the subjec

the iliac crest

The ends of the

Hip Width (Biiliac Diameter).

With the subjects remaining in the same position as for shoulder width, the iliac crests are palpated to locate the points of greatest width. The ends of the caliper are placed on these points for measurement.

Forearm Length (Ra

Maintaining the bo
are asked to flex
toward the chin.
portion of the lat
placed on the tip

Forearm Length (Radio-Stylion).

Maintaining the body position for the upper-arm measurement, subjects are asked to flex their wrists so that the extended fingers are pointing toward the chin. One end of the caliper is then placed on the posterior portion of the lateral epicondyle of the humerus and the other end is placed on the tip of the styloid process of the radius.

Upper-Arm Length

The subjects are

taking the measur

This places the r

90°. After palpa

of the caliper at

portion of the hu

the lateral condy

Upper-Arm Length (Acrom-Radiale).

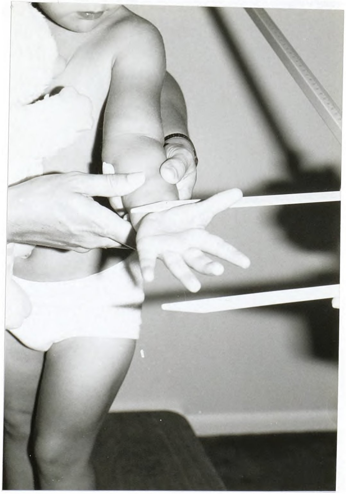
The subjects are asked to stand with their right side toward the person taking the measurements and to place their right hand on their stomach. This places the right brachium at their side with the elbow flexed at 90°. After palpating the landmarks, the anthropometrist places one end of the caliper at the top of the lateral projection of the superior portion of the humerus. The other end is placed in the groove between the lateral condyle of the humerus and the head of the radius.

Measurements Using

Hand Length.

The subjects right
extended and togeth
lateral side of the
the direction the s
held parallel to th
crease to the tip o

Measurements Using the Shortened Anthropometer



Hand Length.

The subjects right hand and fingers are turned palm up, with the fingers extended and together. The elbow is flexed 90° and held next to the lateral side of the trunk with the forearm and hand extended forward in the direction the subject is facing. The shaft of the anthropometer is held parallel to the fingers, and the hand is measured from the wrist crease to the tip of the middle finger.

Upper Extremity

The subjects are

to hold it down

With the anthrop

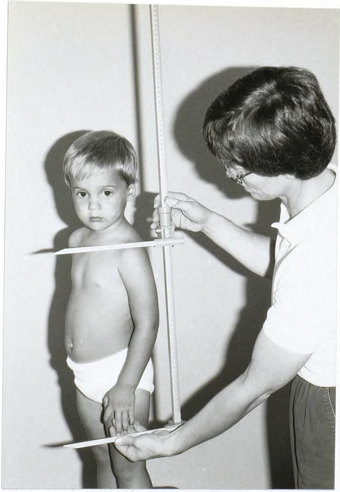
the top of the l

(just below the

the anthropomete

Note: Assistance

able to achieve



Upper Extremity Length.

The subjects are asked to place their hand in an extended position and to hold it down at their side with a straight arm, palm toward the body. With the anthropometer held in the sagittal plane, one end is placed at the top of the lateral projection of the superior portion of the humerus (just below the lateral projection of the acromion). The other end of the anthropometer is placed at the distal end of the middle finger. Note: Assistance is needed with this measurement if the child is not able to achieve a straight arm on his own as illustrated above.

Foot Length.

The subjects are
apart and their
distributed on bo
projection of the
anthropometer is

Foot Length.

The subjects are instructed to stand with their feet shoulder width apart and their right side nearest the anthropometrists, weight evenly distributed on both feet. The right foot is measured from the posterior projection of the heel to the tip of the longest toe. The shaft of the anthropometer is held parallel to the midline of the foot.

Total Leg Length.

With the subjects r

length, they are as

lateral projection

and marked with a s

measured from this

Total Leg Length.

With the subjects remaining in the same standing position as for foot length, they are asked to fold their arms across their chest. The most lateral projection of the greater trochanter of the right leg is located and marked with a small dot using a fine tip marking pen. The length is measured from this mark to the inferior boarder of the right malleolus.

Shank Length.

The subjects stand

small bench so that

edge of the lateral

the same manner as

sagittal plane, and

lateral condyle of

malleolus.

Shank Length.

The subjects stand on their left foot and place their right foot up on a small bench so that a 90° angle is created at the knee. The proximal edge of the lateral condyle of the right tibia is located and marked in the same manner as the trochanter. The anthropometer is held in the sagittal plane, and the leg is measured from the superior aspect of the lateral condyle of the tibia to the inferior boarder of the lateral malleolus.

Standing Height.

The subjects stand on

with the wall. The he

arms hanging free at th

perpendicular to the fl

plane. The subjects ar

sliding bar of the anthr

head with slight pressur

lightly under the subjec

Measurements Using the Full Anthropometer

Standing Height.

The subjects stand on a small bench with heels together and in contact with the wall. The head is positioned in the Frankfort plane with the arms hanging free at their sides. The anthropometer is placed perpendicular to the floor and parallel to the wall in the mid-frontal plane. The subjects are asked to stand as tall as they can while the sliding bar of the anthropometer is brought down on the vertex of the head with slight pressure. The head is stabilized by placing a hand lightly under the subjects jaws.

Trochanteric Height.

The subjects remain

arms over their ches

perpendicular to the

had been placed on t

Trochanteric Height.

The subjects remain standing on the bench and are asked to cross their arms over their chest. With the anthropometer in the sagittal plane and perpendicular to the floor, the sliding bar is lowered to the mark that had been placed on the trochanter for the thigh and leg measurement.

Sitting Height.

The subjects sit o

anthropometer is p

floor. The head is

under the chin. T

the sliding bar of

the head with sligh

Sitting Height.

The subjects sit on the bench with their back against the wall. The anthropometer is placed in the midfrontal plane and perpendicular to the floor. The head is stabilized in the Frankfort plane by light support under the chin. The subjects are asked to sit as tall as they can, and the sliding bar of the anthropometer is brought down on the vertex of the head with slight pressure.

APPENDIX D

Data Collection Forms

Anthropometric Mea

Data Sheet

Weight

Standing Height

Trochanteric Heigh

Sitting Height

Shoulder Width (Bi

Hip Width (Biiliac

Limbs:

Upper-Arm Length (

Forearm Length (Ra

Total Arm Length

Hand Length

Total Leg Length

Leg (Shank) Length

Femur Length (Tota

Name: ____________

Anthropometric Measurement

Subject # ____________

Data Sheet

Birthdate: ____________

Age-Months: ____________

Date: ____________

Weight ____________

Standing Height ____________

Trochanteric Height R: ________ L: ________

Sitting Height ____________

Shoulder Width (Biacromial Diameter) ____________

Hip Width (Biiliac Diameter) ____________

Limbs:	Right	Left
Upper-Arm Length (Acromradiale)		
Forearm Length (Radiostylon)		
Total Arm Length		
Hand Length		
Total Leg Length		
Leg (Shank) Length		
Femur Length (Total Leg - Shank)		

jek:3/86

FILMING R

Time Started: ____

Camera #1: ____

Frame Rate: ____

Lens: ____

Camera-Subject Dis

Camera Calibration

Camera #2: ____

Frame Rate: ____

Lens: ____

Camera-Subject Dis

Camera Calibration

Lighting Condition

Artificial Lights

____

Background: ____

Reference Marks: ____

____

Timing Device: ____

Filming Crew: ____

General Filming Sec

Misc. Comments:

jek:3/86

PROJECT: ________________

DATE: ________________

LOCATION: ________________

FILMING RECORD

Time Started: ______________ Time Completed: ______________

Camera #1: ______________ View: ______________

Frame Rate: __________ Shutter: __________ Exposure Time: ________

Lens: __________ f/stop: ________ Camera Height: ________

Camera-Subject Distance: ______________________

Camera Calibration: ______________________

Camera #2: ______________ View: ______________

Frame Rate: __________ Shutter: __________ Exposure Time: ________

Lens: __________ f/stop: ________ Camera Height: ________

Camera-Subject Distance: ______________________

Camera Calibration: ______________________

Lighting Conditions: ______________________

Artificial Lights (Number & Type): ______________________

____

Background: ______________________

Reference Marks: ______________________

____

Timing Device: ______________________

Filming Crew: ______________________

General Filming Sequence:

Misc. Comments:

jek:3/86

SUBJECT FIL
REC

Subject #	Ti Start

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SUBJECT FILMING SEQUENCE
RECORD

PROJECT ____________________

DATE ________________________

LOCATION ___________________

Subject #	Time Start	Time End	Filming Sequence	Comments

APPENDIX E

Raw Data Tables

Table E-1

Subject Anthropom

STAGE
GENDER
AGE (months)
WEIGHT (kgs)
STANDING HEIGHT
SHOULDER WIDTH
HIP WIDTH
MEAN TROCH. HEIGHT
MEAN TOTAL LEG LENGTH
MEAN FOOT LENGTH

* Stage one male r
standing height.
various segments
conversion facto
segment.

Table E-1

Subject Anthropometric Measurements.

STAGE	1		2		3		4	
GENDER	M*	F	M	F	M	F	M	F
AGE (months)	16	23	37	35	45	35	56	43
WEIGHT (kgs)	9.54	12.34	14.74	16.26	18.2	16.26	22.88	17.78
STANDING HEIGHT	76.7	84.5	93.2	93.8	101.4	93.8	113.4	100.5
SHOULDER WIDTH	17.3	21.9	21.8	21.5	24.1	21.5	26.1	24.1
HIP WIDTH	13.6	16.0	16.5	16.5	17.5	16.5	18.5	16.6
MEAN TROCH. HEIGHT	30.1	36.6	40.55	44.15	44.5	44.15	50.05	47.8
MEAN TOTAL LEG LENGTH	33.3	34.3	38.4	39.5	43.3	39.5	49.6	41.25
MEAN FOOT LENGTH	11.85	13.15	15.35	15.5	16.55	15.5	19.25	15.5

* Stage one male refused to allow measurements other than weight and standing height. Measurements were obtained by hand measuring the various segments in several film views of the subject, using a conversion factor, then averaging the obtained measures for each segment.

Table E-2

<u>Subject Running</u>

MEAN CYCLE LENGTH (cm)	6
MEAN STRIDE LENGTH (cm)	3
TOTAL R-L CYCLES DISTANCE (cm)	10
TOTAL R-L CYCLES TIME (s)	(
MEAN STRIDE TIME (s)	0
MEAN STRIDE RATE (#/s)	3.
RUNNING SPEED (m/s)	1.

Table E-2

Subject Running Descriptors.

	STAGE							
	1		2		3		4	
	M	F	M	F	M	F	M	F
MEAN CYCLE LENGTH (cm)	69.118	87.736	109.907	90.566	158.333	102.264	171.018	169.583
MEAN STRIDE LENGTH (cm)	36.397	45.755	56.481	45.094	79.630	53.302	85.463	85.938
TOTAL R-L CYCLES DISTANCE (cm)	103.677	132.076	168.518	139.622	237.037	158.491	250.000	255.208
TOTAL R-L CYCLES TIME (s)	0.78	0.64	0.74	0.64	0.74	0.63	0.60	0.66
MEAN STRIDE TIME (s)	0.265	0.215	0.255	0.210	0.245	0.210	0.200	0.225
MEAN STRIDE RATE (#/s)	3.77	4.65	3.92	4.76	4.08	4.76	5.00	4.44
RUNNING SPEED (m/s)	1.329	2.064	2.277	2.115	3.203	2.516	4.167	3.867

Table E-3

Segmental Incline
Gender.

STAGE	GENDER	TRUNK
4	M	79.909
	F	75.120
3	M	81.213
	F	76.418
2	M	84.915
	F	78.447
1	M	79.443
	F	79.072

Table E-3

Segmental Inclinations (degs) for Right and Left Touchdown by Stage and Gender.

		RIGHT TOUCHDOWN				LEFT TOUCHDOWN			
STAGE	GENDER	TRUNK	THIGH	SHANK	FOOT	TRUNK	THIGH	SHANK	FOOT
4	M	79.909	116.414	83.780	171.869	79.779	119.800	91.036	172.725
	F	75.120	129.435	83.469	177.627	82.053	115.918	91.777	183.918
3	M	81.213	117.607	94.845	180.000	83.329	106.798	96.115	164.358
	F	76.418	123.689	102.284	197.904	77.382	117.492	101.673	185.274
2	M	84.915	124.055	98.326	178.569	87.447	116.762	99.461	188.749
	F	78.447	127.037	94.999	194.827	81.858	113.962	97.353	189.189
1	M	79.443	113.386	101.560	169.695	84.892	120.966	95.195	166.185
	F	79.072	115.578	104.535	172.876	78.154	113.639	98.654	153.437

Table E-4

Segmental Inclina

by Stage and Gend

		RIG
STAGE	GENDER	TRUNK
4	M	75.611
	F	80.134
3	M	83.069
	F	79.716
2	M	83.255
	F	80.194
1	M	79.416
	F	75.225

* Knee angle = shank incl

Table E-4

Segmental Inclinations (degs) for Right and Left Maximum Leg Extension by Stage and Gender.

		RIGHT MAXIMUM LEG EXTENSION					LEFT MAXIMUM LEG EXTENSION				
STAGE	GENDER	TRUNK	THIGH	SHANK	FOOT	KNEE θ *	TRUNK	THIGH	SHANK	FOOT	KNEE θ *
4	M	75.611	72.285	48.335	139.634	156.000	79.449	58.068	44.957	100.368	166.889
	F	80.134	61.876	44.052	92.725	162.176	77.890	63.641	50.316	91.005	166.675
3	M	83.069	58.393	50.728	122.242	172.335	84.918	62.784	47.095	131.037	164.311
	F	79.716	72.745	60.423	154.759	167.678	76.769	67.378	66.984	154.551	179.606
2	M	83.255	73.344	60.485	134.432	167.141	84.297	76.588	62.331	155.074	165.743
	F	80.194	72.825	64.476	146.822	171.651	81.553	68.120	73.639	158.585	187.519
1	M	79.416	71.566	72.379	142.925	180.813	79.160	78.691	73.645	161.564	174.954
	F	75.225	80.717	80.790	165.752	180.073	78.359	84.088	94.458	166.654	190.370

* Knee angle = shank inclination + (180° - thigh inclination)

Table E-5

Segmental Inclina

Gender.

STAGE	GENDER	TRUNK
4	M	77.997
	F	82.675
3	M	83.069
	F	77.406
2	M	86.100
	F	79.385
1	M	84.892
	F	75.896

ble E-5

gmental Inclinations (degs) for Right and Left Takeoff by Stage and nder.

		RIGHT TAKEOFF				LEFT TAKEOFF			
TAGE	GENDER	TRUNK	THIGH	SHANK	FOOT	TRUNK	THIGH	SHANK	FOOT
4	M	77.997	68.851	35.976	90.649	79.449	58.068	44.957	100.368
	F	82.675	61.699	37.990	70.973	77.890	63.641	50.316	91.005
3	M	83.069	58.393	50.728	122.242	85.524	63.887	46.532	99.091
	F	77.406	70.441	46.365	124.379	81.083	74.575	45.898	128.432
2	M	86.100	72.498	46.220	91.569	85.261	77.593	44.997	87.957
	F	79.385	78.775	37.962	118.675	81.530	63.995	47.096	110.672
1	M	84.892	67.575	46.470	87.797	80.241	81.764	34.904	58.839
	F	75.896	70.865	59.982	107.652	73.398	83.027	64.137	124.290

Table E-6

Segmental Inclina

Stage and Gender.

RIGHT

STAGE	GENDER	TRUNK	T
4	M	77.605	12
	F	78.490	12
3	M	84.648	11
	F	78.980	10
2	M	88.404	13
	F	79.325	104
1	M	81.798	126
	F	79.886	118

* Knee angle = shank incli

able E-6

egmental Inclinations (degs) for Right and Left Minimum Knee Angle by
tage and Gender.

		RIGHT MINIMUM KNEE ANGLE					LEFT MINIMUM KNEE ANGLE				
STAGE	GENDER	TRUNK	THIGH	SHANK	FOOT	KNEE θ *	TRUNK	THIGH	SHANK	FOOT	KNEE θ *
4	M	77.605	128.091	23.648	86.330	75.557	82.652	130.557	25.862	95.295	75.305
	F	78.490	124.089	6.496	87.397	62.407	80.123	113.729	5.663	73.256	71.934
3	M	84.648	113.593	0.469	60.362	66.876	83.375	119.055	33.289	91.878	94.234
	F	78.980	102.533	13.144	75.124	90.611	81.426	98.264	12.527	82.996	94.263
2	M	88.404	133.846	39.045	107.743	85.199	86.651	97.471	12.159	81.472	94.688
	F	79.325	104.037	15.006	82.280	90.969	86.022	99.699	7.370	74.473	87.671
1	M	81.798	126.417	48.655	121.675	102.380	73.196	132.797	52.473	127.997	99.676
	F	79.886	118.442	18.105	93.069	79.663	77.235	118.519	15.492	70.911	76.973

* Knee angle = shank inclination + (180° - thigh inclination)

Table E-7

Segmental Inclin

Height by Stage

		RIGHT
STAGE	GENDER	TRUNK
4	M	80.114
	F	77.750
3	M	85.611
	F	76.280
2	M	85.082
	F	80.126
1	M	79.043
	F	72.492

le E-7

mental Inclinations (degs) for Right and Left Maximum Thigh Segment
ght by Stage and Gender.

		RIGHT MAXIMUM THIGH SEGMENT HEIGHT				LEFT MAXIMUM THIGH SEGMENT HEIGHT			
TAGE	GENDER	TRUNK	THIGH	SHANK	FOOT	TRUNK	THIGH	SHANK	FOOT
4	M	80.114	142.910	74.442	161.377	83.498	149.256	58.461	129.646
	F	77.750	148.298	92.260	170.000	79.077	148.595	83.716	168.472
3	M	85.611	139.899	55.796	139.086	84.409	136.685	109.201	196.556
	F	76.280	138.460	64.901	140.315	77.310	144.687	58.083	145.617
2	M	85.082	146.310	75.123	159.443	82.280	148.877	77.365	168.693
	F	80.126	137.148	79.993	166.152	84.196	132.157	62.578	133.150
1	M	79.043	153.436	85.561	173.019	73.582	144.904	86.533	167.241
	F	72.492	134.999	56.613	118.372	76.866	136.743	63.438	131.059

Table E-8

<u>Segmental Inclina</u>
<u>Forward and Maxin</u>

STAGE	
GENDER	M
RIGHT MAX FWD	
HUMERUS	108.:
FOREARM	251.2
RIGHT MAX BKWD	
HUMERUS	71.1
FOREARM	225.0
LEFT MAX FWD	
HUMERUS	114.56
FOREARM	185.46
LEFT MAX BKWD	
HUMERUS	48.367
FOREARM	130.784

le E-8

mental Inclinations (degs) for Right and Left Arms at Humerus Maximum ward and Maximum Backward Position by Stage and Gender.

STAGE	1		2		3		4	
GENDER	M	F	M	F	M	F	M	F
RIGHT MAX FWD								
HUMERUS	108.113	134.092	88.268	98.638	129.060	90.001	106.157	126.446
FOREARM	251.281	191.536	182.353	203.305	137.718	169.018	231.445	207.804
RIGHT MAX BKWD								
HUMERUS	71.143	22.113	28.544	43.755	39.338	25.498	- 6.864	15.268
FOREARM	225.000	188.130	74.055	106.858	48.630	62.269	90.001	58.351
LEFT MAX FWD								
HUMERUS	114.567	123.687	118.001	119.664	89.349	73.009	120.015	132.014
FOREARM	185.461	150.254	150.001	163.608	159.772	123.298	209.427	213.202
LEFT MAX BKWD								
HUMERUS	48.367	53.693	59.006	23.060	28.422	19.069	16.806	17.288
FOREARM	130.784	74.289	123.111	182.561	44.984	81.117	123.806	75.569

Table E-9

Drawn Midline - Seg

Left Touchdown by S

		STAGE GENDER
RIGHT TOUCHDOWN	LEFT	FOOT
		SHANK
		THIGH
	RIGHT	FOOT
		SHANK
		THIGH
	LEFT	HAND
		FOREARM
		HUMERUS
	RIGHT	HAND
		FOREARM
		HUMERUS
		SHOULDER VARIATION
LEFT TOUCHDOWN	LEFT	FOOT
		SHANK
		THIGH
	RIGHT	FOOT
		SHANK
		THIGH
	LEFT	HAND
		FOREARM
		HUMERUS
	RIGHT	HAND
		FOREARM
		HUMERUS
		SHOULDER VARIATION

e E-9

n Midline - Segment Center-of-Gravity Distance (cm) at Right and Touchdown by Stage and Gender.

		STAGE	1		2		3		4	
		GENDER	M	F	M	F	M	F	M	F
RIGHT TOUCHDOWN	LEFT	FOOT	2.3	5.1	3.9	5.0	0.4	7.4	4.1	8.7
		SHANK	5.3	6.3	5.4	6.0	4.0	8.0	5.9	6.5
		THIGH	6.9	6.8	8.3	7.1	7.7	8.0	7.8	6.5
	RIGHT	FOOT	4.6	6.0	4.3	1.8	9.4	3.0	4.9	4.4
		SHANK	6.2	5.3	4.3	1.9	7.7	4.2	4.9	3.9
		THIGH	6.4	5.7	5.4	5.7	6.3	6.3	5.7	6.5
	LEFT	HAND	5.8	22.6	22.8	10.6	12.5	20.7	2.0	7.2
		FOREARM	9.4	16.0	18.5	14.2	13.5	17.3	10.2	15.6
		HUMERUS	7.4	11.6	14.1	11.4	9.8	10.6	11.9	15.6
	RIGHT	HAND	31.0	29.4	20.6	21.3	28.8	15.0	14.1	15.2
		FOREARM	21.6	17.3	14.1	14.6	21.2	12.7	14.5	13.5
		HUMERUS	13.8	14.3	10.9	12.4	14.4	12.7	13.3	12.0
		SHOULDER VARIATION	R 4.6	R 0.1	R 1.1	R 2.1	R 1.9	R 2.8	R 1.0	0
LEFT TOUCHDOWN	LEFT	FOOT	7.6	5.6	6.6	9.8	4.1	5.3	5.8	7.4
		SHANK	6.5	5.6	5.5	8.9	4.1	5.1	5.8	5.6
		THIGH	6.3	5.6	6.2	7.8	5.2	6.4	5.8	5.6
	RIGHT	FOOT	1.1	5.6	4.1	0.8	0.0	1.0	9.6	2.8
		SHANK	3.3	6.7	7.8	4.1	5.7	4.1	6.7	6.5
		THIGH	6.5	6.9	9.6	6.5	8.1	7.8	6.5	8.3
	LEFT	HAND	21.5	29.2	29.3	24.4	21.1	32.0	15.4	16.6
		FOREARM	14.6	20.8	22.5	19.2	18.7	25.4	16.3	13.7
		HUMERUS	9.8	15.3	16.4	13.7	16.1	15.2	15.0	12.0
	RIGHT	HAND	19.5	25.7	22.9	4.9	22.8	20.3	4.8	15.7
		FOREARM	16.3	19.4	18.0	11.1	15.8	18.2	12.3	16.6
		HUMERUS	11.1	11.1	12.3	11.4	8.1	12.3	12.3	11.1
		SHOULDER VARIATION	0	L 2.8	L 2.1	L 3.0	L 4.9	L 6.0	L 1.5	L 3.3

Table E-10

Drawn Midline -
Left Takeoff by

			STAGE GENDER
RIGHT TAKEOFF	LEFT		FOOT
			SHANK
			THIGH
	RIGHT		FOOT
			SHANK
			THIGH
	LEFT		HAND
			FOREARM
			HUMERUS
	RIGHT		HAND
			FOREARM
			HUMERUS
			SHOULDER VARIATION
LEFT TAKEOFF	LEFT		FOOT
			SHANK
			THIGH
	RIGHT		FOOT
			SHANK
			THIGH
	LEFT		HAND
			FOREARM
			HUMERUS
	RIGHT		HAND
			FOREARM
			HUMERUS
			SHOULDER VARIATION

le E-10

wn Midline - Segment Center-of-Gravity Distance (cm) at Right and t Takeoff by Stage and Gender.

		STAGE	1		2		3		4	
		GENDER	M	F	M	F	M	F	M	F
RIGHT TAKEOFF	LEFT	FOOT	7.6	8.3	6.3	9.9	10.6	9.5	5.6	11.5
		SHANK	6.5	7.4	6.3	8.5	9.6	6.3	5.6	9.2
		THIGH	6.3	6.3	6.3	6.8	6.9	6.3	5.6	6.9
	RIGHT	FOOT	1.1	4.2	2.1	3.1	1.9	1.1	3.6	5.7
		SHANK	3.3	4.9	4.4	3.4	2.9	2.1	3.8	4.6
		THIGH	6.5	5.8	6.3	5.9	4.6	5.9	5.6	8.0
	LEFT	HAND	21.5	27.8	25.5	25.8	27.9	34.8	22.1	20.7
		FOREARM	14.6	19.4	19.8	17.8	24.0	24.9	19.2	18.4
		HUMERUS	9.8	14.6	14.8	12.8	19.2	15.8	14.4	16.1
	RIGHT	HAND	19.6	22.2	16.9	5.4	11.5	14.5	4.8	16.3
		FOREARM	16.3	18.1	16.5	11.6	9.6	14.6	10.6	17.2
		HUMERUS	11.1	11.1	11.6	11.6	7.3	11.6	12.5	14.9
		SHOULDER VARIATION	0	L 2.2	L 2.1	0	L 5.8	L 1.7	L 1.5	L 2.3
LEFT TAKEOFF	LEFT	FOOT	4.2	1.0	3.6	6.8	1.2	3.8	5.5	2.4
		SHANK	6.3	3.2	4.6	7.5	1.0	5.8	4.6	2.9
		THIGH	8.2	5.6	8.0	7.2	3.6	7.1	5.9	4.9
	RIGHT	FOOT	4.4	5.6	3.0	7.5	6.2	5.8	4.1	5.2
		SHANK	6.3	5.0	4.0	7.2	5.9	5.8	3.7	3.6
		THIGH	6.3	5.0	4.4	7.1	5.2	6.2	5.9	4.1
	LEFT	HAND	23.9	6.1	20.4	6.0	13.0	14.0	0.9	8.9
		FOREARM	18.4	7.6	18.8	12.1	13.3	15.4	8.9	13.7
		HUMERUS	10.6	7.1	14.0	11.1	11.6	11.5	11.1	13.0
	RIGHT	HAND	22.6	24.7	20.4	14.3	25.5	17.3	15.7	13.0
		FOREARM	19.0	17.1	12.0	12.4	19.6	15.0	14.8	12.2
		HUMERUS	13.9	12.7	9.2	12.1	13.8	13.1	12.9	10.6
		SHOULDER VARIATION	L 0.2	R 2.2	L 0.6	R 1.5	R 0.6	R 1.5	R 1.8	0

Table E-11

Drawn Midline - Se

Left Minimum Knee A

		STAGE GENDER
RIGHT MINIMUM KNEE ANGLE	LEFT	FOOT
		SHANK
		THIGH
	RIGHT	FOOT
		SHANK
		THIGH
	LEFT	HAND
		FOREARM
		HUMERUS
	RIGHT	HAND
		FOREARM
		HUMERUS
		SHOULDER VARIATION
LEFT MINIMUM KNEE ANGLE	LEFT	FOOT
		SHANK
		THIGH
	RIGHT	FOOT
		SHANK
		THIGH
	LEFT	HAND
		FOREARM
		HUMERUS
	RIGHT	HAND
		FOREARM
		HUMERUS
		SHOULDER VARIATION

e E-11

n Midline - Segment Center-of-Gravity Distance (cm) at Right and
Minimum Knee Angle by Stage and Gender.

		STAGE	1		2		3		4	
		GENDER	M	F	M	F	M	F	M	F
RIGHT MINIMUM KNEE ANGLE	LEFT	FOOT	5.4	1.4	5.2	8.1	1.6	6.6	3.6	4.9
		SHANK	5.4	2.2	4.8	8.1	3.1	6.4	4.8	4.1
		THIGH	7.0	4.2	5.8	7.5	4.9	6.4	8.6	6.2
	RIGHT	FOOT	5.2	11.8	7.7	2.9	0.0	2.9	3.8	-1.6
		SHANK	8.7	8.3	7.3	3.2	7.3	4.7	6.2	4.4
		THIGH	9.4	5.6	7.7	4.9	8.9	7.2	8.8	0.2
	LEFT	HAND	27.2	15.7	29.9	18.7	19.5	31.6	7.7	16.3
		FOREARM	20.6	13.6	22.7	20.3	17.2	25.4	13.8	16.3
		HUMERUS	15.2	10.8	16.2	15.4	14.6	16.0	12.5	14.6
	RIGHT	HAND	22.4	28.6	26.9	12.2	31.7	20.9	15.4	22.0
		FOREARM	18.5	18.8	19.2	12.2	21.9	17.2	17.5	19.5
		HUMERUS	12.6	13.2	10.6	9.9	14.5	11.3	15.4	10.6
		SHOULDER VARIATION	L 1.7	R 1.4	L 2.9	L 1.6	L 3.2	L 2.1	R 1.0	L 2.4
LEFT MINIMUM KNEE ANGLE	LEFT	FOOT	7.2	11.9	4.4	5.3	3.6	5.6	3.2	8.9
		SHANK	10.5	9.9	7.1	6.8	5.6	7.0	5.7	8.3
		THIGH	10.2	7.0	8.9	8.3	7.6	8.3	8.1	6.9
	RIGHT	FOOT	6.2	2.9	0.9	5.7	1.7	5.2	3.4	2.8
		SHANK	6.2	3.2	2.7	6.0	3.1	5.6	4.9	2.8
		THIGH	7.2	4.6	5.3	6.2	5.3	7.6	7.2	5.6
	LEFT	HAND	25.6	26.4	25.7	19.6	18.1	26.8	16.9	14.6
		FOREARM	19.5	18.3	20.4	16.0	15.4	21.3	18.7	13.9
		HUMERUS	11.3	12.6	13.3	11.0	10.0	14.4	14.6	11.1
	RIGHT	HAND	27.5	22.9	21.5	6.8	25.1	16.5	16.2	22.2
		FOREARM	20.9	17.1	16.0	12.8	20.1	14.6	17.1	18.1
		HUMERUS	15.4	12.0	11.5	13.6	15.3	12.0	14.8	11.1
		SHOULDER VARIATION	R 2.0	0	R 0.7	R 1.8	R 2.1	R 0.9	R 0.8	L 1.4

Table E-12

Drawn Midline - Se

Left Maximum Thigh

		STAGE / GENDER
RIGHT MAXIMUM THIGH SEGMENT HEIGHT	LEFT	FOOT
		SHANK
		THIGH
	RIGHT	FOOT
		SHANK
		THIGH
	LEFT	HAND
		FOREARM
		HUMERUS
	RIGHT	HAND
		FOREARM
		HUMERUS
		SHOULDER VARIATION
LEFT MAXIMUM THIGH SEGMENT HEIGHT	LEFT	FOOT
		SHANK
		THIGH
	RIGHT	FOOT
		SHANK
		THIGH
	LEFT	HAND
		FOREARM
		HUMERUS
	RIGHT	HAND
		FOREARM
		HUMERUS
		SHOULDER VARIATION

Table E-12

Drawn Midline - Segment Center-of-Gravity Distance (cm) at Right and Left Maximum Thigh Segment Height by Stage and Gender.

		STAGE	1		2		3		4	
		GENDER	M	F	M	F	M	F	M	F
RIGHT MAXIMUM THIGH SEGMENT HEIGHT	LEFT	FOOT	3.9	1.4	3.8	6.0	0.7	6.0	5.6	1.6
		SHANK	4.4	2.8	4.4	6.3	0.7	6.4	4.6	2.9
		THIGH	5.4	5.3	6.4	6.3	4.2	7.6	6.3	4.9
	RIGHT	FOOT	8.9	9.7	9.6	7.4	9.3	6.9	1.8	5.7
		SHANK	8.9	6.2	7.3	3.0	7.4	6.9	1.8	3.6
		THIGH	7.0	4.9	6.5	3.3	6.9	6.9	4.1	4.9
	LEFT	HAND	21.7	9.7	21.2	7.5	11.7	17.7	1.3	8.1
		FOREARM	19.6	11.1	18.3	12.1	11.7	16.9	10.0	11.4
		HUMERUS	15.2	9.4	13.5	9.8	10.6	11.7	12.0	13.0
	RIGHT	HAND	21.3	26.9	26.4	20.6	28.2	20.8	17.6	11.7
		FOREARM	17.0	18.6	18.3	13.9	21.7	16.9	14.8	11.4
		HUMERUS	11.7	11.8	12.3	11.6	13.8	13.3	13.7	9.8
		SHOULDER VARIATION	L 0.6	R 0.7	0	R 3.0	R 0.7	R 2.0	R 0.9	L 1.3
LEFT MAXIMUM THIGH SEGMENT HEIGHT	LEFT	FOOT	8.4	9.3	8.1	11.9	8.3	6.7	8.1	10.1
		SHANK	9.8	8.0	4.9	10.1	6.9	6.7	7.3	7.3
		THIGH	9.0	7.4	4.9	7.2	5.8	7.1	7.3	5.7
	RIGHT	FOOT	5.7	4.7	1.5	3.6	1.1	5.3	3.1	3.2
		SHANK	6.2	4.7	2.3	4.3	1.4	4.4	4.4	4.8
		THIGH	6.4	5.6	5.4	5.1	4.2	5.3	6.5	5.1
	LEFT	HAND	23.6	27.4	26.3	22.4	14.2	29.1	19.8	15.2
		FOREARM	15.2	19.4	21.1	14.9	15.3	30.5	19.5	12.7
		HUMERUS	9.2	12.6	15.1	10.7	14.2	15.1	15.3	10.8
	RIGHT	HAND	16.0	20.1	16.1	0.0	6.9	14.2	14.6	5.7
		FOREARM	16.4	14.9	14.5	8.7	8.2	12.1	17.9	12.7
		HUMERUS	12.5	10.3	9.8	10.9	10.8	8.9	15.3	9.1
		SHOULDER VARIATION	R 0.8	L 1.0	L 2.4	0	L 2.8	L 3.6	R 0.3	L 2.3

Table E-13

Linear Displacem
Touchdown to Tak

STAGE	GENDER	TRUNK
4	M	53.950
	F	51.724
3	M	47.561
	F	43.240
2	M	61.649
	F	46.482
1	M	37.875
	F	44.331

Table E-13

Linear Displacement (cm) of Centers of Mass for Leg Segments from Touchdown to Takeoff by Stage and Gender.

		RIGHT				LEFT			
STAGE	GENDER	TRUNK	THIGH	SHANK	FOOT	TRUNK	THIGH	SHANK	FOOT
4	M	53.950	45.866	30.713	18.059	57.835	45.262	29.100	18.105
	F	51.724	41.558	25.113	16.966	46.216	38.397	27.868	20.414
3	M	47.561	38.872	26.702	21.824	46.620	38.156	23.871	15.520
	F	43.240	36.545	24.899	19.252	41.764	35.850	24.752	18.780
2	M	61.649	50.089	41.036	31.421	50.699	47.681	37.474	28.498
	F	46.482	44.354	32.183	25.514	39.582	35.662	23.137	19.669
1	M	37.875	36.597	31.849	29.201	45.739	45.614	39.248	33.198
	F	44.331	39.018	26.498	21.024	30.225	28.350	24.709	20.058

Table E-14

Linear Displaceme
Takeoff to Minimu

STAGE	GENDER	TRUNK
4	M	39.803
	F	44.038
3	M	39.292
	F	22.080
2	M	31.402
	F	13.242
1	M	15.986
	F	24.539

Table E-14

Linear Displacement (cm) of Centers of Mass for Leg Segments from Takeoff to Minimum Knee Angle by Stage and Gender.

		RIGHT				LEFT			
STAGE	GENDER	TRUNK	THIGH	SHANK	FOOT	TRUNK	THIGH	SHANK	FOOT
4	M	39.803	55.763	66.025	66.891	61.642	76.404	89.245	91.044
	F	44.038	55.599	66.166	69.128	40.896	49.327	50.052	50.380
3	M	39.292	49.286	56.566	58.982	38.502	57.308	55.612	57.686
	F	22.080	27.357	31.335	28.569	19.387	23.331	27.776	25.778
2	M	31.402	40.032	49.641	53.173	14.241	16.809	18.381	18.026
	F	13.242	17.301	20.947	20.108	20.645	26.118	30.025	28.421
1	M	15.986	21.682	26.628	27.931	12.688	17.269	23.444	29.164
	F	24.539	33.486	37.943	41.912	32.555	37.198	39.795	39.188

Table E-15

Linear Displacem
Minimum Knee Ang

STAGE	GENDER	TRUNK
4	M	25.602
	F	32.347
3	M	19.687
	F	15.828
2	M	9.450
	F	21.059
1	M	9.865
	F	5.375

Table E-15

Linear Displacement (cm) of Centers of Mass for Leg Segments from Minimum Knee Angle to Maximum Thigh Segment Height by Stage and Gender.

		RIGHT				LEFT			
STAGE	GENDER	TRUNK	THIGH	SHANK	FOOT	TRUNK	THIGH	SHANK	FOOT
4	M	25.602	24.816	39.998	55.362	12.248	13.798	19.273	27.943
	F	32.347	35.733	46.706	62.855	27.254	32.195	42.776	56.067
3	M	19.687	26.142	32.130	41.886	28.415	34.197	45.113	61.398
	F	15.828	20.089	28.306	36.498	19.472	27.401	34.774	42.003
2	M	9.450	10.527	16.752	24.271	28.116	33.702	46.821	59.510
	F	21.059	26.811	35.073	46.557	18.490	22.896	30.521	40.266
1	M	9.865	11.660	17.950	24.103	8.445	8.627	11.045	17.112
	F	5.375	6.170	11.173	16.722	11.258	14.235	18.661	25.473

Table E-16

Linear Displacem
Maximum Thigh Se

STAGE	GENDER	TRUNK
4	M	38.688
	F	28.528
3	M	33.641
	F	22.697
2	M	32.283
	F	13.985
1	M	15.798
	F	20.644

Table E-16

Linear Displacement (cm) of Centers of Mass for Leg Segments from Maximum Thigh Segment Height to Touchdown by Stage and Gender.

		RIGHT				LEFT			
STAGE	GENDER	TRUNK	THIGH	SHANK	FOOT	TRUNK	THIGH	SHANK	FOOT
4	M	38.688	36.262	37.748	44.179	38.052	37.253	35.410	48.474
	F	28.528	26.773	25.835	24.073	17.234	17.167	18.763	20.711
3	M	33.641	31.191	36.452	45.331	28.256	26.614	24.283	24.520
	F	22.697	25.030	30.808	39.735	16.600	16.966	20.752	26.928
2	M	32.283	30.274	30.305	36.349	19.078	16.028	18.246	23.355
	F	13.985	14.625	16.505	19.037	15.362	16.163	17.623	24.054
1	M	15.798	13.816	15.109	18.051	13.051	15.338	16.731	19.035
	F	20.644	20.857	23.907	33.761	14.737	13.301	16.211	25.957

Table E-17

Linear Displace
Humerus Maximum
Gender.

STAGE	GENDER
4	M
	F
3	M
	F
2	M
	F
1	M
	F

Table E-17

Linear Displacement (cm) of Centers of Mass for Arm Segments from Humerus Maximum Forward to Maximum Backward Position by Stage and Gender.

		RIGHT			LEFT		
STAGE	GENDER	TRUNK	HUMERUS	FOREARM	TRUNK	HUMERUS	FOREARM
4	M	59.158	70.847	56.784	70.502	59.177	48.022
	F	63.50.	54.699	41.213	97.488	77.297	66.855
3	M	71.792	65.140	55.990	65.889	61.255	58.194
	F	49.961	49.087	35.158	38.706	34.417	35.911
2	M	58.826	54.064	44.550	51.101	50.609	44.103
	F	51.947	44.628	38.968	68.280	61.843	58.104
1	M	22.021	17.730	16.728	50.945	58.805	56.361
	F	53.890	43.007	37.464	51.354	47.922	52.210

Table E-18

Angular Displace
to Takeoff by St

STAGE	GENDER	
4	M	-4 (-
	F	-6 (-
3	M	-5 (-
	F	-53 (-0
2	M	-51 (-0
	F	-48. (-0.
1	M	-45. (-0.
	F	-44. (-0.

Table E-18

Angular Displacement in Degrees (Radians) of Leg Segments from Touchdown to Takeoff by Stage and Gender.

		RIGHT			LEFT		
STAGE	GENDER	THIGH	SHANK	FOOT	THIGH	SHANK	FOOT
4	M	-47.563 (-0.829)	-47.804 (-0.833)	-81.220 (-1.418)	-61.732 (-1.075)	-46.034 (-0.804)	-72.357 (-1.263)
	F	-67.766 (-1.183)	-45.479 (0.794)	-102.681 (-1.861)	-52.340 (-0.912)	-41.461 (-0.724)	-92.913 (-1.620)
3	M	-59.214 (-1.034)	-44.099 (-0.769)	-57.758 (-1.009)	-47.185 (-0.823)	-48.525 (-0.848)	-81.705 (-1.426)
	F	-53.253 (-0.932)	-55.919 (-0.975)	-66.743 (-1.282)	-42.917 (-0.747)	-55.775 (-0.971)	-56.856 (-0.994)
2	M	-51.557 (-0.901)	-52.106 (-0.909)	-87.000 (-1.519)	-39.169 (-0.682)	-57.554 (-0.942)	-100.798 (-1.758)
	F	-48.262 (-0.840)	-57.028 (-0.995)	-76.152 (-1.328)	-49.877 (-0.875)	-50.257 (-0.878)	-78.517 (-1.368)
1	M	-45.811 (-0.797)	-55.080 (-0.960)	-81.898 (-1.427)	-39.202 (-0.686)	-60.281 (-1.052)	-107.346 (-1.872)
	F	-44.713 (-0.780)	-44.553 (-0.778)	-65.197 (-1.138)	-30.612 (-0.535)	- 4.517 (-0.603)	-29.147 (-0.508)

Table E-19

Angular Displace
to Minimum Knee

STAGE	GENDER	
4	M	5 (
	F	6 (
3	M	5 (
	F	3 (
2	M	6 (1
	F	28 (0
1	M	58 (1
	F	47 (0

Table E-19

Angular Displacement in Degrees (Radians) of Leg Segments from Takeoff to Minimum Knee Angle by Stage and Gender.

		RIGHT			LEFT		
STAGE	GENDER	THIGH	SHANK	FOOT	THIGH	SHANK	FOOT
4	M	59.239 (1.034)	-12.330 (-0.214)	- 4.319 (-0.076)	72.480 (1.267)	-19.149 (-0.323)	-4.985 (-0.090)
	F	62.420 (1.083)	-31.494 (-0.547)	16.424 (0.287)	50.088 (0.874)	-44.653 (-0.078)	-8.131 (-0.142)
3	M	55.202 (0.963)	-50.259 (-0.881)	-60.880 (-1.081)	55.168 (0.964)	-13.293 (-0.231)	-7.213 (-0.125)
	F	32.092 (0.560)	-33.244 (-0.580)	-49.255 (-0.860)	23.689 (0.413)	-33.371 (-0.584)	-45.436 (-0.794)
2	M	61.342 (1.010)	-7.175 (-0.125)	16.174 (0.283)	19.878 (0.347)	-32.838 (-0.572)	-6.485 (-0.113)
	F	28.262 (0.440	-22.950 (-0.400)	-36.395 (-0.635)	35.704 (0.623)	-39.726 (-0.694)	-36.199 (-0.631)
1	M	58.842 (1.027)	2.185 (0.039)	33.886 (0.591)	51.033 (0.890)	17.569 (0.307)	-69.158 (-1.206)
	F	47.577 (0.829)	-41.877 (-0.731)	-14.583 (-0.254)	35.492 (0.621)	-48.645 (-0.849)	-53.379 (-0.934)

Table E-20

Angular Displacer
Knee Angle to Max

STAGE	GENDER	
4	M	1 (
	F	2 (
3	M	26 (0
	F	35 (0
2	M	12. (0.
	F	33. (0.
1	M	27. (0.
	F	16.5 (0.2

Table E-20

Angular Displacement in Degrees (Radians) of Leg Segments from Minimum Knee Angle to Maximum Thigh Segment Height by Stage and Gender.

		RIGHT			LEFT		
STAGE	GENDER	THIGH	SHANK	FOOT	THIGH	SHANK	FOOT
4	M	14.819 (0.258)	50.774 (0.886)	74.597 (1.309)	18.699 (0.326)	32.600 (0.569)	34.354 (0.600)
	F	24.209 (0.423)	86.764 (1.509)	82.594 (1.422)	34.866 (0.609)	78.052 (1.361)	95.216 (1.661)
3	M	26.304 (0.458)	55.327 (0.966)	78.724 (1.374)	17.630 (0.258)	75.912 (1.321)	104.678 (1.832)
	F	35.927 (0.626)	51.757 (0.904)	65.191 (1.138)	46.423 (0.709)	45.556 (0.794)	62.671 (1.095)
2	M	12.464 (0.217)	36.708 (0.629)	51.700 (0.903)	51.406 (0.898)	65.206 (1.138)	87.218 (1.523)
	F	33.111 (0.578)	64.987 (1.135)	83.872 (1.464)	32.458 (0.566)	55.208 (0.963)	58.677 (1.025)
1	M	27.019 (0.472)	36.906 (0.644)	51.344 (0.896)	12.107 (0.211)	34.060 (0.592)	39.244 (0.684)
	F	16.557 (0.224)	38.508 (0.672)	25.303 (0.441)	18.223 (0.319)	47.946 (0.837)	60.148 (1.049)

Table E-21

<u>Angular Displace</u>
<u>Thigh Segment He</u>

STAGE	GENDER	
4	M	-1 (-
	F	-1 (-
3	M	-21 (-(
	F	-18 (-0
2	M	-27 (-0.
	F	-15. (-0.
1	M	-37. (-0.
	F	-17. (-0.

Table E-21

Angular Displacement in Degrees (Radians) of Leg Segments from Maximum Thigh Segment Height to Touchdown by Stage and Gender.

		RIGHT			LEFT		
STAGE	GENDER	THIGH	SHANK	FOOT	THIGH	SHANK	FOOT
4	M	-18.416 (-0.321)	20.389 (0.356)	9.615 (1.167)	-25.905 (-0.453)	29.671 (0.517)	42.412 (0.740)
	F	-19.709 (-0.345)	-5.441 (0.097)	4.131 (0.073)	-16.168 (-0.282)	11.481 (0.201)	17.855 (0.311)
3	M	-21.798 (-0.379)	48.276 (0.774)	58.593 (1.025)	-19.868 (-0.348)	-5.827 (-0.102)	-4.987 (-0.086)
	F	-18.997 (-0.332)	43.299 (0.755)	62.990 (1.100)	-11.536 (-0.202)	35.358 (0.618)	40.686 (0.713)
2	M	-27.737 (-0.484)	16.260 (0.284)	10.962 (0.192)	-6.536 (-0.116)	8.673 (0.151)	33.581 (0.587)
	F	-15.820 (-0.276)	17.244 (0.301)	20.894 (0.368)	-18.891 (-0.330)	36.421 (0.636)	53.461 (0.932)
1	M	-37.238 (-0.649)	19.184 (0.335)	-0.144 (-0.003)	-30.097 (-0.525)	12.310 (0.215)	18.285 (0.319)
	F	-17.241 (-0.301)	46.629 (0.813)	60.801 (1.062)	-24.836 (-0.433)	40.601 (0.709)	45.254 (0.790)

Table E-22

Angular Displace
Maximum Forward

STAGE	GENDER
4	M
	F
3	M
	F
2	M
	F
1	M
	F

Table E-22

Angular Displacement in Degrees (Radians) of Arm Segments from Humerus Maximum Forward to Maximum Backward Position by Stage and Gender.

		RIGHT		LEFT	
STAGE	GENDER	HUMERUS	FOREARM	HUMERUS	FOREARM
4	M	-113.023 (-1.972)	-141.435 (2.471)	-103.207 (-1.801)	-85.952 (-1.500)
	F	-125.342 (-2.177)	-142.966 (-2.601)	-105.623 (-1.844)	-132.355 (-2.361)
3	M	-86.206 (-1.653)	-79.237 (-1.384)	-72.222 (-1.261)	-110.522 (-1.930)
	F	-7.711 (-0.134)	-72.937 (-1.275)	-56.866 (-0.984)	-42.811 (-0.747)
2	M	-59.724 (-1.070)	-108.296 (-1.889)	-49.142 (-0.858)	-22.615 (-0.394)
	F	-54.885 (-0.957)	-96.444 (-1.684)	-92.305 (-1.569)	23.271 (0.406)
1	M	-37.030 (-0.644)	-26.821 (-0.468)	-68.201 (-1.154)	-54.677 (-0.959)
	F	-112.069 (-1.893)	-3.415 (-0.060)	-88.945 (-1.550)	-57.005 (-0.994)

Table E-23

Distance (cm) Be

Center of Gravit

STAGE GENDER	M
TOUCHDOWN	
RIGHT	8.5
LEFT	9.11

* Negative number indica

Table E-23

Distance (cm) Between the Downward Vertical Projection of the Total Body Center of Gravity and the Support Foot at Right and Left Touchdown.

STAGE	1		2		3		4	
GENDER	M	F	M	F	M	F	M	F
TOUCHDOWN								
RIGHT	8.529	10.189	14.815	10.755	10.182	11.132	2.963	8.333
LEFT	9.118	- 5.660*	20.370	10.377	10.963	9.434	5.741	12.083

* Negative number indicates foot landed behind the downward vertical projection of the body center of gravity.

Table E-24

Temporal (s) Obs

Stage and Gender

STAGE GENDER LEG MEAN	R
Touchdown to Maximum Leg Extension	.1
Maximum Leg Extension to Takeoff	.0
Takeoff to Minimum Knee Angle	.1(
Minimum Knee Angle to Maximum Thigh Segment Height	.07
Maximum Thigh Segment Height to Touchdown	.09

Table E-24

Temporal (s) Observations for One Running Cycle of Right and Left Leg by Stage and Gender.

STAGE	1					2					3					4				
GENDER	M		F			M		F			M		F			M		F		
LEG	R	L	R	L		R	L	R	L		R	L	R	L		R	L	R	L	
MEAN					$\bar{X}$					$\bar{X}$					$\bar{X}$					$\bar{X}$
Touchdown to Maximum Leg Extension	.19	.16	.16	.09	.15	.17	.16	.17	.14	.16	.17	.14	.15	.15	.15	.11	.15	.15	.15	.14
Maximum Leg Extension to Takeoff	.08	.14	.08	.06	.09	.04	.06	.04	.05	.05	.00	.02	.03	.03	.02	.03	.00	.01	.00	.01
Takeoff to Minimum Knee Angle	.10	.09	.12	.14	.11	.13	.06	.06	.08	.08	.14	.13	.08	.07	.10	.11	.15	.13	.16	.14
Minimum Knee Angle to Maximum Thigh Segment Height	.07	.04	.03	.06	.05	.04	.13	.09	.08	.08	.07	.10	.07	.08	.08	.06	.03	.09	.08	.06
Maximum Thigh Segment Height to Touchdown	.09	.09	.09	.06	.08	.13	.07	.06	.07	.08	.11	.09	.09	.07	.09	.09	.09	.07	.05	.07

APPENDIX F

Statistical Analyses Tables

Table F-1

Analysis for Stac

Left Touchdown.

	1	
	R	L
THIGH	114.480	117.30
SHANK	103.050	96.92
FOOT	171.290	159.81

* Significance in right sh

Table F-2

Analysis for Gend

Left Touchdown.

THIGH
SHANK
FOOT

Table F-1

Analysis for Stage Effect on Segmental Inclinations (deg) at Right and Left Touchdown.

	STAGE MEANS									
	1		2		3		4		F	p
	R	L	R	L	R	L	R	L	(6,2)	
THIGH	114.480	117.300	125.550	115.360	120.650	112.140	122.920	117.860	0.69	.6914
SHANK	103.050	96.924	96.660	98.410	98.560	98.899	83.620	91.406	30.66	.0391*
FOOT	171.290	159.810	186.700	188.970	188.950	174.820	174.750	178.320	1.37	.4799

* Significance in right shank inclination: 1 2 3 4

Table F-2

Analysis for Gender Effect on Segmental Inclinations (deg) at Right and Left Touchdown.

	GENDER MEANS					
	MALE		FEMALE		F	p
	R	L	R	L	(2,2)	
THIGH	117.870	115.250	123.930	116.080	2.08	.3245
SHANK	94.628	95.452	96.322	97.364	2.49	.2864
FOOT	175.030	173.000	185.810	177.950	3.43	.2259

Table F-3

Analysis for Sta
Left Takeoff.

	1	
	R	L
THIGH	69.220	82.39
SHANK	53.226	49.52
FOOT	97.720	91.56

Table F-4

Analysis for Gend
Left Takeoff.

THIGH
SHANK
FOOT

Table F-3

Analysis for Stage Effect on Segmental Inclinations (deg) at Right and Left Takeoff.

	STAGE MEANS									
	1		2		3		4		F	p
	R	L	R	L	R	L	R	L	(6,2)	
THIGH	69.220	82.395	75.636	70.794	64.417	69.231	65.275	60.854	0.76	.6659
SHANK	53.226	49.520	42.091	46.046	48.546	46.215	36.983	47.636	2.60	.3040
FOOT	97.720	91.560	105.120	99.310	123.310	113.760	80.810	95.690	0.68	.6983

Table F-4

Analysis for Gender Effect on Segmental Inclinations (deg) at Right and Left Takeoff.

	GENDER MEANS					
	MALE		FEMALE		F	p
	R	L	R	L	(2,2)	
THIGH	66.829	70.328	70.445	71.309	0.28	.7788
SHANK	44.848	42.847	45.575	51.862	3.56	.2192
FOOT	98.060	86.560	105.420	113.600	1.24	.4466

Table F-5

Analysis for St

Left Maximum Le

	1	
	R	L
THIGH	76.141	81.3
SHANK	76.584	84.0
FOOT	154.341	164.1
ACTUAL KNEE ANGLE*	180.443	182.6

* Actual knee angle = sha

Table F-6

Analysis for Ger

Left Maximum Leg

THIGH
SHANK
FOOT
ACTUAL KNEE ANGLE*

* Actual knee angle = shan

** Significance for left s

Table F-5

Analysis for Stage Effect on Segmental Inclinations (deg) at Right and Left Maximum Leg Extension.

	STAGE MEANS									
	1		2		3		4			
	R	L	R	L	R	L	R	L	F (6,2)	p
THIGH	76.141	81.389	73.084	72.354	65.569	65.081	67.080	60.854	1.20	.5211
SHANK	76.584	84.051	62.480	67.985	55.575	57.039	46.193	47.636	3.21	.2563
FOOT	154.341	164.109	140.630	156.829	138.500	142.794	116.186	95.686	9.39	.0994
ACTUAL KNEE ANGLE*	180.443	182.662	169.396	176.631	170.006	171.958	159.090	166.782	3.61	.2329

* Actual knee angle = shank inclination + (180° - thigh inclination).

Table F-6

Analysis for Gender Effect on Segmental Inclinations (deg) at Right and Left Maximum Leg Extension.

	GENDER MEANS					
	MALE		FEMALE			
	R	L	R	L	F (2,2)	p
THIGH	68.897	69.033	72.041	70.807	0.17	.8546
SHANK	57.982	57.007	62.435	71.349	31.70	.0306**
FOOT	134.810	137.011	140.016	142.699	0.47	.6797
ACTUAL KNEE ANGLE*	169.072	167.974	170.394	181.042	3.65	.2148

* Actual knee angle = shank inclination + (180° - thigh inclination).
** Significance for left shank only

Table F-7

Analysis for St
Touchdown and T

	R	1
TOUCHDOWN	79.257	8
TAKEOFF	80.394	7

Table F-8

Analysis for Gen
Touchdown and Ta

TOUCHDOWN	
TAKEOFF	

Table F-7

Analysis for Stage Effect on Trunk Inclination (deg) at Right and Left Touchdown and Takeoff.

	STAGE MEANS									
	1		2		3		4		F	p
	R	L	R	L	R	L	R	L	(6,2)	
TOUCHDOWN	79.257	81.523	81.681	84.652	78.815	80.355	77.514	80.916	0.59	.7403
TAKEOFF	80.394	76.812	82.742	83.395	80.247	83.303	80.346	78.669	6.73	.1349

able F-8

nalysis for Gender Effect on Trunk Inclination (deg) at Right and Left ouchdown and Takeoff.

	GENDER MEANS					
	MALE		FEMALE		F	p
	R	L	R	L	(2,2)	
TOUCHDOWN	81.370	83.862	77.264	79.862	6.13	.1402
TAKEOFF	83.014	82.619	78.840	78.475	11.38	.0808

Table F-9

Analysis for St

Left Minimum Kn

	1	
	R	L
THIGH	122.429	125.6
SHANK	33.380	33.9
FOOT	107.370	99.4
ACTUAL KNEE ANGLE*	91.020	88.3

* Actual knee angle = shan

Table F-10

Analysis for Gen

Left Minimum Kne

THIGH
SHANK
FOOT
ACTUAL KNEE ANGLE*

* Actual knee angle = shank

able F-9

alysis for Stage Effect on Segmental Inclinations (deg) at Right and eft Minimum Knee Angle.

	STAGE MEANS									
	1		2		3		4		F	p
	R	L	R	L	R	L	R	L	(6,2)	
THIGH	122.429	125.658	118.941	98.585	108.063	108.659	126.090	122.143	9.51	.0982
SHANK	33.380	33.982	27.030	9.764	6.810	22.908	15.070	15.762	0.67	.7037
FOOT	107.370	99.450	95.010	77.970	67.740	87.440	86.860	84.280	0.60	.7361
ACTUAL KNEE ANGLE*	91.020	88.324	88.080	91.179	78.740	94.248	68.980	73.619	0.93	.6000

Actual knee angle = shank inclination + (180° - thigh inclination).

ble F-10

alysis for Gender Effect on Segmental Inclinations (deg) at Right and ft Minimum Knee Angle.

	GENDER MEANS					
	MALE		FEMALE		F	p
	R	L	R	L	(2,2)	
THIGH	125.487	119.970	112.275	107.553	36.60	.0266
SHANK	27.954	30.946	13.188	10.263	3.71	.2122
FOOT	94.030	99.160	84.470	75.410	1.40	.4158
ACTUAL KNEE ANGLE*	82.500	90.976	80.910	82.710	1.81	.3563

tual knee angle = shank inclination + (180° - thigh inclination).

Table F-11

Analysis for Sta
Left Maximum Thi

	1 R	L
THIGH	144.217	140.823
SHANK	71.090	74.990
FOOT	145.700	149.150

Table F-12

Analysis for Gend
Left Maximum Thig

THIGH
SHANK
FOOT

le F-11

lysis for Stage Effect on Segmental Inclinations (deg) at Right and
t Maximum Thigh Segment Height.

	STAGE MEANS									
	1		2		3		4		F	p
	R	L	R	L	R	L	R	L	(6,2)	
GH	144.217	140.823	141.729	140.517	139.179	140.686	145.604	148.925	0.14	.9734
NK	71.090	74.990	77.560	69.970	60.350	83.640	83.350	71.090	0.24	.9246
T	145.700	149.150	162.800	150.920	139.700	171.110	164.690	149.060	0.22	.9351

e F-12

ysis for Gender Effect on Segmental Inclinations (deg) at Right and
Maximum Thigh Segment Height.

	GENDER MEANS					
	MALE		FEMALE		F	p
	R	L	R	L	(2,2)	
THIGH	145.639	144.930	139.730	140.540	0.46	.6856
SHANK	72.730	82.890	73.440	66.950	0.40	.7151
FOOT	158.230	165.530	148.710	144.590	0.39	.7204

Table F-13

Analysis for Sta
Left Humerus Max

	I R	
FORWARD		
HUMERUS	121.100	119
FOREARM	221.680	167
BACKWARD		
HUMERUS	46.630	51
FOREARM	206.560	102
HUMERUS RANGE OF MOTION	78.470	68.

* Significance in right f

ble F-13

alysis for Stage Effect on Segmental Inclinations (deg) at Right and ft Humerus Maximum Forward and Backward.

	STAGE MEANS									
	1		2		3		4		F	p
	R	L	R	L	R	L	R	L	(6,2)	
RWARD										
HUMERUS	121.100	119.120	93.450	118.832	109.530	81.179	116.300	126.014	37.74	.0206
FOREARM	221.680	167.860	192.830	156.800	153.370	141.530	219.620	211.310	1.12	.5422
CKWARD										
HUMERUS	46.630	51.030	36.150	41.030	32.420	23.750	4.200	17.050	1.31	.4927
FOREARM	206.560	102.540	90.460	152.840	55.450	63.050	74.180	99.690	561.51	.0018*
MERUS NGE OF TION	78.470	68.100	57.800	77.800	77.110	57.430	112.100	108.970	1.12	.5414

Significance in right forearm inclination: 1 2 3 4

Table F-14

Analysis for Ge
Left Humerus Ma

FORWARD	
HUMERUS	
FOREARM	
BACKWARD	
HUMERUS	
FOREARM	
HUMERUS RANGE OF MOTION	

ble F-14

alysis for Gender Effect on Segmental Inclinations (deg) at Right and eft Humerus Maximum Forward and Backward.

	GENDER MEANS					
	MALE		FEMALE		F	p
	R	L	R	L	(2,2)	
FORWARD						
HUMERUS	107.900	110.483	112.290	112.093	0.04	.9626
FOREARM	200.830	176.170	192.920	162.590	0.37	.7302
BACKWARD						
HUMERUS	33.040	38.150	26.660	28.280	0.79	.5599
FOREARM	109.420	105.670	103.900	103.380	4.29	.1889
HUMERUS RANGE OF MOTION	74.860	72.330	87.890	83.820	0.64	.6112

Table F-15

Analysis for Sta
Vertical Projecti
Foot at Right an

HEIGHT
TOUCHDOWN
RIGHT
LEFT

* Distance = percent of sta

Table F-16

Analysis for Gend
Vertical Projecti
Foot at Right and

HEIG
TOUCHD
RIG
LEF

* Distance = percent of stan

le F-15

lysis for Stage Effect on the Distance (cm) Between the Downward
:ical Projection of the Total Body Center of Gravity and the Support
: at Right and Left Touchdown.

	STAGE MEANS					
	1	2	3	4	F (6,2)	p
HEIGHT	80.6	93.5	97.6	107		
TOUCHDOWN					0.780	.6552
RIGHT	9.359 (12)*	12.785 (14)	10.657 (11)	5.648 (5)		
LEFT	1.729 (2)	15.373 (16)	11.198 (12)	8.912 (8)		

ance = percent of standing height.

e F-16

ysis for Gender Effect on the Distance (cm) Between the Downward
ical Projection of the Total Body Center of Gravity and the Support
 at Right and Left Touchdown.

	GENDER MEANS			
	MALE	FEMALE	F (2,2)	p
HEIGHT	96.2	93.2		
TOUCHDOWN			1.41	.4156
RIGHT	9.122 (9)*	10.102 (11)		
LEFT	12.048 (12)	6.558 (7)		

nce = percent of standing height.

Table F-17

Analysis for St

Limb Segments C

STAGE TOUCHDOWN SIDE HEIGHT	R
SUPPORT SIDE	
THIGH	6.08 (7)
SHANK	5.74 (7)
FOOT	5.31 (6)
HUMERUS	14.05 (17
FOREARM	19.47 (24)
HAND	30.21 (37)
NONSUPPORT SIDE	
THIGH	6.841 (8)
SHANK	5.810 (7)
FOOT	3.712 (5)
HUMERUS	9.454 (12)
FOREARM	12.703 (16)
HAND	14.180 (18)
SHOULDER VARIATION	2.337 (3)

* Distance = percent of s

Table F-17

Analysis for Stage Effect on the Distance (cm) Between Drawn Midline and Limb Segments Centers of Gravity for Right and Left Touchdown.

STAGE	1		2		3		4		F	p
TOUCHDOWN SIDE	R	L	R	L	R	L	R	L	(6,2)	
HEIGHT	80.6		93.5		97.6		107			
SUPPORT SIDE										
THIGH	6.083	5.930	5.557	6.975	6.340	5.777	6.129	5.658	0.528	.7695
	(7)*	(7)	(6)	(7)	(6)	(6)	(6)	(5)		
SHANK	5.742	6.039	3.150	7.237	5.957	4.593	4.415	6.658	0.921	.6042
	(7)	(7)	(3)	(8)	(6)	(5)	(4)	(6)		
FOOT	5.314	6.581	3.061	8.156	6.189	4.696	4.632	6.582	0.228	.9004
	(6)	(8)	(3)	(8)	(6)	(5)	(4)	(6)		
HUMERUS	14.058	12.530	11.646	15.023	13.545	15.628	12.636	13.509	0.441	.8151
	(17)	(16)	(12)	(16)	(14)	(16)	(12)	(13)		
FOREARM	19.475	17.699	14.343	20.860	16.911	22.050	14.011	15.014	3.167	.2594
	(24)	(22)	(15)	(22)	(17)	(22)	(13)	(14)		
HAND	30.218	25.344	20.973	26.842	21.918	26.547	14.676	16.012	3.339	.2483
	(37)	(31)	(22)	(29)	(22)	(27)	(14)	(15)		
NONSUPPORT SIDE										
THIGH	6.841	6.733	7.679	8.066	7.857	7.957	7.153	7.429	0.275	.9075
	(8)	(8)	(8)	(9)	(8)	(8)	(7)	(7)		
SHANK	5.810	6.601	5.734	5.925	6.031	4.894	6.231	6.601	0.066	.9954
	(7)	(8)	(6)	(6)	(6)	(5)	(6)	(6)		
FOOT	3.712	3.321	4.441	2.455	3.887	0.512	6.396	6.194	0.291	.8987
	(5)	(4)	(5)	(3)	(4)	(.5)	(6)	(6)		
HUMERUS	9.454	11.099	12.744	11.836	10.182	10.210	13.767	11.099	0.345	.6383
	(12)	(14)	(14)	(13)	(10)	(10)	(13)	(10)		
FOREARM	12.703	17.874	16.377	14.542	15.387	17.002	12.947	14.473	4.885	.1796
	(16)	(22)	(17)	(16)	(16)	(17)	(12)	(14)		
HAND	14.180	22.630	16.737	13.911	16.595	21.522	4.611	10.261	0.393	.8416
	(18)	(28)	(18)	(15)	(17)	(22)	(4)	(9)		
SHOULDER VARIATION	2.337	1.389	1.608	1.187	2.334	2.746	0.512	2.433	0.324	.8805
	(3)	(2)	(2)	(1)	(2)	(3)	(.4)	(2)		

* Distance = percent of standing height.

Table F-18

Analysis for Ge
and Limb Segmen

GENDER TOUCHDOWN SIDE HEIGHT
SUPPORT SIDE
THIGH
SHANK
FOOT
HUMERUS
FOREARM
HAND
NONSUPPORT SIDE
THIGH
SHANK
FOOT
HUMERUS
FOREARM
HAND
SHOULDER VARIATION

* Distance = percent of sta

le F-18

lysis for Gender Effect on the Distance (cm) Between Drawn Midline
Limb Segments Centers of Gravity for Right and Left Touchdown.

GENDER	MALE		FEMALE		F	p
TOUCHDOWN SIDE	R	L	R	L	(2,2)	
HEIGHT	96.2		93.2			
SUPPORT SIDE						
THIGH	5.989 (6)*	5.855 (6)	6.065 (6)	6.314 (7)	0.219	.8201
SHANK	5.791 (6)	5.472 (6)	3.841 (4)	6.291 (6)	4.104	.1959
FOOT	5.821 (6)	5.999 (6)	3.777 (4)	7.008 (7)	0.523	.6567
HUMERUS	13.101 (14)	14.317 (15)	12.842 (14)	14.028 (15)	0.039	.9629
FOREARM	17.861 (18)	18.036 (19)	14.508 (16)	19.776 (21)	2.519	.2841
HAND	23.668 (25)	21.834 (23)	20.224 (22)	25.538 (27)	0.397	.7159
NONSUPPORT SIDE						
THIGH	7.659 (8)	7.705 (8)	7.106 (8)	7.388 (8)	0.669	.5993
SHANK	5.176 (5)	5.867 (6)	6.727 (7)	5.325 (6)	1.205	.4534
FOOT	2.673 (3)	3.700 (4)	6.545 (7)	2.541 (3)	3.258	.2349
HUMERUS	10.794 (11)	10.954 (11)	12.279 (13)	11.469 (12)	0.362	.7342
FOREARM	12.902 (13)	15.603 (16)	15.785 (17)	16.343 (18)	6.229	.1383
HAND	10.781 (11)	17.520 (18)	15.281 (16)	16.642 (18)	0.693	.5906
SHOULDER VARIATION	2.158 (2)	2.116 (2)	1.237 (1)	1.761 (2)	0.924	.5199

tance = percent of standing height.

Table F-19

Analysis for St

Limb Segments C

STAGE TAKEOFF SIDE HEIGHT	R
SUPPORT SIDE	
THIGH	6.1[illegible] (8)
SHANK	4.06 (5)
FOOT	2.62 (3)
HUMERUS	11.09 (14
FOREARM	17.18 (21
HAND	20.84 (26)
NONSUPPORT SIDE	
THIGH	6.277 (8)
SHANK	6.941 (8)
FOOT	7.971 (10)
HUMERUS	12.183 (15)
FOREARM	17.005 (21)
HAND	24.650 (31)
SHOULDER VARIATION	1.111 (1)

* Distance = percent of st

.e F-19

ysis for Stage Effect on the Distance (cm) Between Drawn Midline and
 Segments Centers of Gravity for Right and Left Takeoff.

STAGE	1		2		3		4		F	p
OFF SIDE	R	L	R	L	R	L	R	L	(6,2)	
HEIGHT	80.6		93.5		97.6		107			
ORT SIDE										
THIGH	6.177 (8)*	6.902 (8)	6.142 (6)	7.613 (8)	5.263 (5)	5.368 (6)	6.812 (6)	5.397 (5)	0.279	.9055
SHANK	4.061 (5)	4.749 (6)	3.917 (4)	6.066 (6)	2.498 (2)	3.391 (3)	5.142 (5)	3.774 (4)	1.749	.4075
FOOT	2.627 (3)	2.618 (3)	2.586 (3)	5.189 (6)	1.489 (2)	2.502 (3)	4.701 (4)	3.993 (4)	2.183	.3471
HUMERUS	11.099 (14)	8.822 (11)	11.587 (12)	12.568 (13)	9.460 (10)	11.562 (12)	13.723 (13)	12.050 (11)	1.473	.4567
FOREARM	17.180 (21)	12.981 (16)	14.015 (15)	15.417 (16)	12.091 (12)	14.354 (15)	13.911 (13)	11.266 (10)	0.357	.8617
HAND	20.849 (26)	14.966 (18)	11.165 (12)	13.201 (14)	14.003 (14)	13.536 (14)	7.577 (7)	4.934 (5)	0.397	.8394
UPPORT SIDE										
THIGH	6.277 (8)	5.699 (7)	6.567 (7)	5.740 (6)	6.628 (7)	5.684 (6)	6.237 (6)	4.991 (5)	0.083	.9921
SHANK	6.941 (8)	5.699 (7)	7.417 (8)	5.615 (6)	7.974 (8)	5.853 (6)	7.387 (7)	3.637 (3)	0.217	.9387
FOOT	7.971 (10)	5.002 (6)	8.098 (9)	5.267 (6)	10.039 (10)	5.998 (6)	8.537 (8)	4.635 (4)	0.093	.9896
HUMERUS	12.183 (15)	13.396 (17)	13.765 (15)	10.624 (11)	17.532 (18)	13.417 (14)	15.259 (14)	11.755 (11)	0.738	.6731
FOREARM	17.005 (21)	18.045 (22)	18.849 (20)	12.173 (13)	24.475 (25)	17.275 (18)	18.813 (18)	13.493 (13)	2.454	.3175
HAND	24.650 (31)	23.637 (29)	25.695 (27)	17.347 (18)	31.360 (32)	21.398 (22)	21.405 (20)	14.361 (13)	1.183	.5251
DER ITION	1.111 (1)	1.182 (1)	1.056 (1)	1.053 (1)	3.729 (4)	1.059 (1)	1.919 (.2)	1.181 (.1)	0.133	.9769

tance = percent of standing height.

Table F-20

Analysis for G
and Limb Segme

GENDER TAKEOFF SIDE HEIGHT
SUPPORT SIDE
THIGH
SHANK
FOOT
HUMERUS
FOREARM
HAND
NONSUPPORT SIDE
THIGH
SHANK
FOOT
HUMERUS
FOREARM
HAND
SHOULDER VARIATION

* Distance = percent of st

e F-20

ysis for Gender Effect on the Distance (cm) Between Drawn Midline
Limb Segments Centers of Gravity for Right and Left Takeoff.

GENDER	MALE		FEMALE		F	p
TAKEOFF SIDE	R	L	R	L	(2,2)	
HEIGHT	96.2		93.2			
SUPPORT SIDE						
THIGH	5.762 (6)*	6.440 (7)	6.436 (7)	6.200 (7)	0.397	.7159
SHANK	3.606 (4)	4.141 (4)	4.203 (4)	4.849 (5)	1.699	.3705
FOOT	2.194 (2)	3.631 (4)	3.508 (4)	3.520 (4)	2.589	.2787
HUMERUS	10.627 (11)	11.804 (12)	12.307 (13)	10.698 (11)	4.352	.1869
FOREARM	13.241 (14)	14.835 (15)	15.357 (16)	12.174 (13)	1.366	.4226
HAND	13.200 (14)	14.547 (15)	13.619 (15)	8.772 (9)	0.522	.6571
NONSUPPORT SIDE						
THIGH	6.284 (6)	5.464 (6)	6.571 (7)	5.596 (6)	0.218	.8210
SHANK	7.012 (7)	4.991 (5)	7.848 (8)	5.411 (6)	0.134	.8820
FOOT	7.524 (8)	4.431 (5)	9.798 (10)	6.020 (6)	0.994	.5015
HUMERUS	14.554 (15)	12.455 (13)	14.816 (16)	12.091 (13)	0.035	.9665
FOREARM	19.420 (20)	16.331 (17)	20.151 (22)	14.161 (15)	1.528	.3955
HAND	24.267 (25)	21.041 (22)	27.288 (29)	17.330 (19)	1.697	.3708
SHOULDER VARIATION	2.355 (2)	0.810 (.8)	1.553 (2)	1.299 (2)	0.207	.8283

tance = percent of standing height.

Table F-21

Analysis for St
Limb Segments C

STAGE MIN KNEE ANGLE SIDE HEIGHT	R
SUPPORT SIDE	
THIGH	5.5 (7
SHANK	3.82 (5)
FOOT	3.14 (4)
HUMERUS	13.02 (16)
FOREARM	17.132 (21)
HAND	21.434 (26)
NONSUPPORT SIDE	
THIGH	7.452 (9)
SHANK	8.514 (11)
FOOT	8.511 (10)
HUMERUS	12.902 (16)
FOREARM	18.614 (23)
HAND	25.501 (32)
SHOULDER VARIATION	1.564 (2)

* Distance = percent of standi

e F-21

ysis for Stage Effect on the Distance (cm) Between Drawn Midline and Segments Centers of Gravity for Right and Left Minimum Knee Angle.

STAGE	1		2		3		4		F	p
NEE ANGLE SIDE	R	L	R	L	R	L	R	L	(6,2)	
HEIGHT	80.6		93.5		97.6		107			
RT SIDE										
THIGH	5.562 (7)*	5.813 (7)	6.624 (7)	5.752 (6)	5.614 (6)	6.429 (6)	7.416 (7)	6.355 (6)	0.838	.6340
SHANK	3.828 (5)	4.673 (6)	6.469 (7)	4.346 (5)	4.720 (5)	4.301 (4)	4.436 (4)	3.828 (4)	1.769	.4042
FOOT	3.142 (4)	4.501 (6)	6.661 (7)	3.308 (4)	4.091 (4)	3.422 (4)	4.266 (4)	3.096 (3)	0.710	.6851
HUMERUS	13.025 (16)	13.682 (17)	15.800 (17)	12.551 (13)	15.306 (16)	13.648 (14)	13.567 (13)	12.954 (12)	0.164	.9641
FOREARM	17.132 (21)	19.022 (24)	21.509 (23)	14.392 (15)	21.318 (22)	17.372 (18)	15.053 (14)	17.564 (16)	0.466	.8019
HAND	21.434 (26)	25.153 (31)	22.811 (24)	14.128 (15)	25.529 (26)	20.797 (21)	11.976 (11)	19.211 (18)	0.413	.8306
PPORT SIDE										
THIGH	7.452 (9)	8.607 (11)	6.285 (7)	8.582 (9)	8.056 (8)	7.979 (8)	4.548 (4)	7.537 (7)	0.226	.9338
SHANK	8.514 (11)	10.195 (13)	5.280 (6)	6.941 (7)	6.014 (6)	6.291 (6)	5.272 (5)	7.012 (6)	1.525	.4474
OOT	8.511 (10)	9.528 (12)	5.310 (6)	4.856 (6)	1.434 (1)	4.579 (5)	1.110 (1)	6.070 (6)	0.855	.6276
UMERUS	12.902 (16)	11.919 (15)	10.248 (11)	12.157 (13)	12.869 (13)	12.210 (12)	12.977 (12)	12.873 (12)	0.212	.9415
OREARM	18.614 (23)	18.873 (23)	15.716 (17)	18.193 (19)	19.579 (20)	18.339 (19)	18.506 (17)	16.294 (15)	0.148	.9709
AND	25.501 (32)	26.003 (32)	19.559 (21)	22.664 (24)	26.309 (27)	22.432 (23)	18.668 (17)	15.747 (15)	0.404	.8353
ER ION	1.564 (2)	1.024 (1)	2.255 (2)	1.259 (1)	2.650 (3)	1.504 (2)	1.700 (2)	1.101 (1)	0.107	.9856

ce = percent of standing height.

Table F-22

Analysis for Ge
and Limb Segmen
Angle.

GENDER MIN KNEE ANGLE SI HEIGHT
SUPPORT SIDE
THIGH
SHANK
FOOT
HUMERUS
FOREARM
HAND
NONSUPPORT SIDE
THIGH
SHANK
FOOT
HUMERUS
FOREARM
HAND
SHOULDER VARIATION

* Distance = percent of stand

F-22

sis for Gender Effect on the Distance (cm) Between Drawn Midline
imb Segments Centers of Gravity for Right and Left Minimum Knee
.

GENDER	MALE		FEMALE		F	p
MIN KNEE ANGLE SIDE	R	L	R	L	(2,2)	
HEIGHT	96.2		93.2			
SUPPORT SIDE						
THIGH	6.564 (7)*	6.231 (6)	6.044 (6)	5.943 (6)	0.128	.8865
SHANK	4.535 (5)	4.185 (4)	5.192 (6)	4.388 (5)	0.508	.6632
FOOT	3.977 (4)	3.029 (3)	5.238 (6)	4.135 (4)	0.143	.8746
HUMERUS	14.262 (15)	14.243 (15)	14.223 (15)	12.174 (13)	0.820	.5490
FOREARM	18.607 (19)	18.519 (19)	18.899 (20)	15.565 (17)	1.445	.4090
HAND	20.325 (21)	22.565 (23)	20.550 (22)	17.079 (18)	0.648	.6067
NONSUPPORT SIDE						
THIGH	8.707 (9)	8.721 (9)	4.463 (5)	7.632 (8)	2.720	.2689
SHANK	7.368 (8)	7.198 (7)	5.172 (6)	8.021 (9)	3.153	.2408
FOOT	4.189 (4)	4.617 (5)	3.994 (4)	7.899 (8)	2.850	.2597
HUMERUS	13.260 (14)	12.302 (13)	11.237 (12)	12.277 (13)	0.946	.5139
FOREARM	19.292 (20)	18.496 (19)	16.916 (18)	17.354 (19)	0.638	.6106
HAND	24.106 (25)	21.576 (22)	20.913 (22)	21.847 (23)	0.110	.9012
SHOULDER VARIATION	2.209 (2)	1.414 (1)	1.876 (2)	1.030 (1)	0.153	.8676

ce = percent of standing height.

Table F-23

Analysis for St
Limb Segments C
Segment Height.

STAGE MAX THIGH SIDE HEIGHT	R
SUPPORT SIDE	
THIGH	5.3 (7)
SHANK	3.5 (4)
FOOT	2.65 (3)
HUMERUS	12.33 (15)
FOREARM	15.33 (19)
HAND	15.731 (19)
NONSUPPORT SIDE	
THIGH	5.909 (7)
SHANK	7.581 (9)
FOOT	9.318 (11)
HUMERUS	11.772 (15)
FOREARM	17.784 (22)
HAND	24.124 (30)
SHOULDER VARIATION	0.763 (.9)

* Distance = percent of s

: F-23

ysis for Stage Effect on the Distance (cm) Between Drawn Midline and Segments Centers of Gravity for Right and Left Maximum Thigh ent Height.

AGE	1		2		3		4		F	p
IIGH SIDE	R	L	R	L	R	L	R	L	(6,2)	
IGHT	80.6		93.5		97.6		107			
RT SIDE										
THIGH	5.356 (7)*	5.975 (7)	6.339 (7)	5.217 (6)	5.873 (6)	4.745 (5)	5.582 (5)	5.784 (5)	10.136	.0925
SHANK	3.563 (4)	5.416 (7)	5.377 (6)	3.310 (4)	3.539 (4)	2.913 (3)	3.774 (3)	4.600 (4)	1.657	.4230
FOOT	2.651 (3)	5.211 (6)	4.938 (5)	2.542 (3)	3.341 (3)	3.217 (3)	3.586 (3)	3.127 (3)	2.853	.2821
HUMERUS	12.331 (15)	11.391 (14)	11.630 (12)	10.309 (11)	11.144 (11)	9.853 (10)	12.513 (12)	12.199 (11)	0.213	.9410
FOREARM	15.338 (19)	15.623 (19)	15.165 (16)	11.580 (12)	14.305 (15)	10.131 (10)	10.683 (10)	15.272 (14)	0.517	.7753
HAND	15.731 (19)	18.046 (23)	14.346 (15)	8.049 (9)	14.702 (15)	10.570 (11)	4.712 (4)	10.165 (10)	0.244	.9244
PORT SIDE										
HIGH	5.909 (7)	8.221 (10)	4.927 (5)	6.059 (6)	6.951 (7)	6.466 (7)	4.473 (4)	6.507 (7)	0.541	.7633
HANK	7.581 (9)	8.916 (11)	5.161 (6)	7.508 (8)	7.168 (7)	6.844 (7)	2.713 (2)	7.329 (7)	0.843	.6320
OOT	9.318 (11)	8.828 (11)	8.501 (9)	10.002 (11)	8.109 (8)	7.538 (8)	3.770 (4)	9.128 (8)	0.650	.7113
JMERUS	11.772 (15)	10.895 (14)	11.957 (13)	12.919 (14)	13.531 (14)	14.625 (15)	11.719 (11)	13.022 (12)	0.228	.9332
OREARM	17.784 (22)	17.294 (21)	16.069 (17)	18.027 (19)	19.301 (20)	22.900 (23)	13.086 (12)	16.085 (15)	0.578	.7450
ND	24.124 (30)	25.493 (32)	23.499 (25)	24.394 (26)	24.545 (25)	21.635 (22)	14.635 (14)	17.514 (16)	0.524	.7718
R ON	0.763 (.9)	0.920 (1)	1.507 (2)	1.219 (1)	1.355 (1)	3.163 (3)	1.113 (1)	1.301 (1)	1.118	.5430

tance = percent of standing height.

Table F-24

Analysis for Ge
and Limb Segmen
Segment Height.

GENDER MAX THIGH SID HEIGHT
SUPPORT SIDE
THIGH
SHANK
FOOT
HUMERUS
FOREARM
HAND
NONSUPPORT SIDE
THIGH
SHANK
FOOT
HUMERUS
FOREARM
HAND
SHOULDER VARIATION

* Distance = percent of

e F-24

ysis for Gender Effect on the Distance (cm) Between Drawn Midline
Limb Segments Centers of Gravity for Right and Left Maximum Thigh
ent Height.

GENDER	MALE		FEMALE		F	p
MAX THIGH SIDE	R	L	R	L	(2,2)	
HEIGHT	96.2		93.2			
SUPPORT SIDE						
THIGH	5.567 (6)	5.597 (6)	6.008 (6)	5.264 (6)	12.249	.0755
SHANK	3.529 (4)	3.550 (4)	4.598 (5)	4.569 (5)	0.503	.6654
FOOT	3.507 (4)	2.850 (3)	3.750 (4)	4.199 (4)	3.275	.2339
HUMERUS	12.817 (13)	12.092 (13)	10.992 (12)	9.783 (10)	2.458	.2892
FOREARM	14.887 (15)	14.235 (15)	12.858 (14)	12.068 (13)	0.325	.7549
HAND	13.979 (14)	13.413 (14)	10.766 (12)	10.002 (11)	0.186	.8434
NONSUPPORT SIDE						
THIGH	6.128 (6)	6.760 (7)	5.004 (5)	6.866 (7)	0.575	.6348
SHANK	6.364 (7)	7.243 (7)	4.948 (5)	8.056 (9)	0.389	.7201
FOOT	7.411 (8)	8.248 (9)	7.437 (8)	8.248 (9)	0.430	.6992
HUMERUS	12.871 (13)	13.448 (14)	11.618 (12)	12.283 (13)	0.726	.5795
FOREARM	17.935 (19)	17.772 (18)	15.185 (16)	19.381 (21)	1.161	.4627
HAND	23.363 (24)	20.976 (22)	20.039 (22)	23.542 (25)	0.500	.6667
SHOULDER VARIATION	0.575 (.6)	1.589 (2)	1.749 (2)	1.714 (2)	3.989	.2004

:ance = percent of standing height.

Table F-25

Analysis for S

Right and Left

SUPPO

R

L

NONSU

R

L

Table F-26

Analysis for St

SUPPORT

NONSUPP

ble F-25

alysis for Stage Effect on Time (s) in Support and Nonsupport for ght and Left Leg Running Cycles.

	STAGE 1	2	3	4	F (6,2)	p
SUPPORT					25.000	.0390
RIGHT	0.230	0.210	0.170	0.150		
LEFT	0.225	0.200	0.175	0.140		
NONSUPPORT					0.076	.9936
RIGHT	0.250	0.255	0.275	0.280		
LEFT	0.240	0.245	0.270	0.280		

ble F-26

alysis for Stage Effect on Total Time (s) in Support and Nonsupport.

	STAGE 1	2	3	4	F (3,3)	p
SUPPORT	0.675	0.615	0.530	0.445	0.297	.8956
NONSUPPORT	0.060	0.085	0.155	0.188		

Table F-27

Analysis for Ge
Right and Left

S

N

Table F-28

Analysis for Gen

SU

NO

le F-27

alysis for Gender Effect on Time (s) in Support and Nonsupport for
ght and Left Leg Running Cycles.

	GENDER MALE	FEMALE	F (2,2)	p
SUPPORT			26.000	.0370
RIGHT	0.195	0.185		
LEFT	0.202	0.167		
NONSUPPORT			0.855	.5392
RIGHT	0.285	0.245		
LEFT	0.267	0.250		

le F-28

lysis for Gender Effect on Total Time (s) in Support and Nonsupport.

	GENDER MALE	FEMALE	F (1,3)	p
SUPPORT	0.607	0.525	0.786	.5598
NONSUPPORT	0.120	0.122		

Table F-29

Analysis for St
for Right and L

SUPPORT
RIG
LEF
NONSUPP
RIGH
LEFT

Table F-30

Analysis for Stag
Nonsupport.

SUPPORT
NONSUPPORT

able F-29

nalysis for Stage Effect on Percent of Cycle in Support and Nonsupport or Right and Left Leg.

	STAGE 1	2	3	4	$F_{(6,2)}$	p
SUPPORT					0.511	.7784
RIGHT	47.500	45.500	38.000	35.500		
LEFT	47.500	45.000	40.000	33.000		
NONSUPPORT					0.511	.7784
RIGHT	52.500	54.500	62.000	64.500		
LEFT	52.500	55.000	60.000	67.000		

ole F-30

alysis for Stage Effect on Total Percent of Cycles in Support and nsupport.

	STAGE 1	2	3	4	$F_{(3,3)}$	p
SUPPORT	90.500	87.500	78.000	70.500	1.552	.3634
NONSUPPORT	9.500	12.500	22.000	29.500		

Table F-31

Analysis for (
for Right and

Table F-32

Analysis for Ge
Nonsupport.

ıble F-31

ıalysis for Gender Effect on Percent of Cycle in Support and Nonsupport
ɔr Right and Left Leg.

	GENDER MALE	FEMALE	F (2,2)	p
SUPPORT			1.955	.3384
RIGHT	40.000	43.250		
LEFT	42.500	40.250		
NONSUPPORT			1.955	.3384
RIGHT	60.000	56.750		
LEFT	57.500	59.750		

ıble F-32

ıalysis for Gender Effect on Total Percent of Cycles in Support and
ınsupport.

	GENDER MALE	FEMALE	F (1,3)	p
SUPPORT	82.250	81.000	0.029	.8754
NONSUPPORT	17.750	19.000		

Table F-33

Analysis of Sta
of Leg Segments
for Each Leg.

STAGE LIMB SIDE HEIGHT	
1.‡	
THIGH	37.8 (4
SHANK	29.1 (3
FOOT	25.1 (3
2.‡	
THIGH	27.5 (3
SHANK	32.2 (40
FOOT	34.92 (43
3.‡	
THIGH	8.91 (11
SHANK	14.56 (18)
FOOT	20.412 (25)
4.‡	
THIGH	17.336 (22)
SHANK	19.508 (24)
FOOT	25.910 (32)

‡ 1. = Touchdown to Takeo
2. = Takeoff to Minimum
3. = Minimum Knee Angle
4. = Maximum Thigh Segm

le F-33

<u>lysis of Stage Effect on Linear Displacement (cm) of Centers of Mass Leg Segments for Selected Periods During One Complete Running Cycle Each Leg.</u>

STAGE	1		2		3		4			
LIMB SIDE	R	L	R	L	R	L	R	L	F	p
HEIGHT	80.6		93.5		97.6		107		(6,2)	
.*										
THIGH	37.802	36.982	47.221	41.671	37.708	37.003	43.712	41.829	2.12	.3553
	(47)**	(46)	(50)	(44)	(39)	(38)	(41)	(39)		
SHANK	29.173	31.978	36.609	30.305	25.800	24.311	27.913	28.484	3.23	.2550
	(36)	(40)	(39)	(32)	(26)	(25)	(26)	(27)		
FOOT	25.112	26.628	28.407	24.083	20.538	17.150	17.512	19.259	15.01	.0638
	(31)	(33)	(30)	(26)	(21)	(18)	(16)	(18)		
.*										
THIGH	27.580	27.230	28.670	21.460	38.320	40.320	55.680	62.870	0.52	.7728
	(34)	(34)	(31)	(23)	(39)	(41)	(52)	(58)		
SHANK	32.290	31.620	35.290	24.200	43.950	41.690	66.100	69.650	0.70	.6910
	(40)	(39)	(38)	(26)	(45)	(43)	(62)	(65)		
FOOT	34.920	34.180	36.640	23.220	43.780	41.730	68.010	70.710	0.64	.7171
	(43)	(42)	(39)	(25)	(45)	(43)	(64)	(66)		
*										
THIGH	8.915	11.431	18.669	28.299	23.115	30.799	30.274	22.996	0.68	.6961
	(11)	(14)	(20)	(30)	(24)	(32)	(28)	(21)		
SHANK	14.561	14.850	25.912	38.670	30.218	39.940	43.352	31.020	1.22	.5149
	(18)	(18)	(28)	(41)	(31)	(41)	(40)	(29)		
FOOT	20.412	21.290	35.414	49.890	39.192	51.700	59.108	42.000	1.27	.5034
	(25)	(26)	(38)	(53)	(40)	(53)	(55)	(39)		
*										
THIGH	17.336	14.319	22.449	16.095	28.110	21.790	31.517	27.210	0.48	.7924
	(22)	(18)	(24)	(17)	(29)	(22)	(29)	(25)		
SHANK	19.508	16.471	23.405	17.934	33.630	22.517	31.791	27.086	0.42	.8252
	(24)	(20)	(25)	(19)	(34)	(23)	(30)	(25)		
FOOT	25.910	22.490	27.690	23.700	42.530	25.720	34.130	34.590	0.31	.8870
	(32)	(28)	(30)	(25)	(44)	(26)	(32)	(32)		

= Touchdown to Takeoff.
= Takeoff to Minimum Knee Angle.
= Minimum Knee Angle to Maximum Thigh Segment Height.
= Maximum Thigh Segment Height to Touchdown.

** = Percent of standing height.

Table F-34

<u>Analysis of</u>
<u>of Leg Segm</u>
<u>for Each Le</u>

GENDE
LIMB
HEIGH
1.*
S
F
2.*
THI
SHA
FOOT
3.*
THIGH
SHANK
FOOT
4.*
THIGH
SHANK
FOOT

* 1. = Touchdown to Takeo
2. = Takeoff to Minimum
3. = Minimum Knee Angle
4. = Maximum Thigh Segme

Table F-34

Analysis of Gender Effect on Linear Displacement (cm) of Centers of Mass of Leg Segments for Selected Periods During One Complete Running Cycle for Each Leg.

GENDER	MALE		FEMALE			
LIMB SIDE	R	L	R	L	F	p
HEIGHT	96.2		93.2		(2,2)	
1.*						
THIGH	42.856 (44)**	44.178 (46)	40.369 (43)	34.565 (37)	6.49	.1335
SHANK	32.575 (34)	32.423 (34)	27.173 (30)	25.116 (27)	5.35	.1574
FOOT	25.126 (26)	23.830 (25)	20.689 (22)	19.730 (21)	17.81	.0532
2.*						
THIGH	41.691 (43)	41.950 (44)	33.436 (36)	33.990 (36)	0.34	.7484
SHANK	49.715 (52)	46.670 (48)	39.098 (42)	36.910 (40)	0.52	.6572
FOOT	51.740 (54)	48.980 (51)	39.930 (43)	35.940 (38)	0.63	.6151
3.*						
THIGH	18.286 (19)	22.581 (23)	22.201 (24)	24.182 (26)	0.17	.8515
SHANK	26.707 (28)	30.563 (32)	30.314 (32)	31.683 (34)	0.17	.8579
FOOT	36.405 (38)	41.490 (43)	40.658 (44)	40.950 (44)	0.13	.8853
4.*						
THIGH	27.896 (29)	23.808 (25)	21.821 (23)	15.899 (17)	1.33	.4283
SHANK	29.903 (31)	23.667 (25)	24.264 (26)	18.337 (20)	0.75	.5727
FOOT	35.977 (37)	28.846 (30)	29.157 (31)	24.410 (26)	0.23	.8102

1. = Touchdown to Takeoff.
2. = Takeoff to Minimum Knee Angle.
3. = Minimum Knee Angle to Maximum Thigh Segment Height.
4. = Maximum Thigh Segment Height to Touchdown.

** = Percent of standing height.

Table F-35

<u>Analysis of</u>
<u>Leg Segment</u>
<u>Each Leg.</u>

STAGE LIMB SIDE	R
1.* THIGH	-45. (-0.
SHANK	-49. (-0.
FOOT	-73.5 (-1.2
2.* THIGH	53.2 (0.9
SHANK	-19.8 (-0.3
FOOT	9.65 (0.16
3.* THIGH	21.78 (0.34
SHANK	37.71 (0.65
FOOT	38.32 (0.66
4.* THIGH	-27.239 (-0.475
SHANK	32.910 (0.574)
FOOT	30.330 (0.530)

* 1. = Touchdown to
2. = Takeoff to Mi
3. = Minimum Knee
4. = Maximum Thigh

Table F-35

Analysis of Stage Effect on Angular Displacement in Degrees (Radians) of Leg Segments for Selected Periods During One Complete Running Cycle for Each Leg.

STAGE		1		2		3		4		F	p
LIMB SIDE		R	L	R	L	R	L	R	L	(6,2)	
1.*	THIGH	-45.626	-34.907	-49.909	-44.523	-56.233	-45.051	-57.664	-57.036	1.358	.4823
		(-0.788)	(0.610)	(0.870)	(0.778)	(-0.983)	(-0.785)	(-1.006)	(-0.994)	(1.314)	(.4926)
	SHANK	-49.816	-47.399	-54.567	-53.905	-50.009	-52.150	-46.641	-43.747	0.180	.9568
		(-0.869)	(-0.828)	(-0.952)	(-0.910)	(-0.872)	(-0.910)	(-0.814)	(-0.764)	(0.303)	(.8922)
	FOOT	-73.550	-68.250	-81.580	-89.650	-62.250	-69.280	-93.950	-82.630	0.883	.6175
		(-1.282)	(-1.190)	(-1.424)	(-1.563)	(-1.146)	(-1.210)	(-1.640)	(-1.442)	(0.500)	(.7842)
2.*	THIGH	53.210	43.260	44.800	27.790	43.650	39.430	60.830	61.280	1.074	.5556
		(0.928)	(0.756)	(0.725)	(0.485)	(0.762)	(0.688)	(1.058)	(1.070)	(1.195)	(.5520)
	SHANK	-19.850	-15.540	-15.070	-36.280	-41.750	-23.330	-21.910	-31.900	0.550	.7584
		(-0.346)	(-0.271)	(-0.262)	(-0.633)	(-0.730)	(-0.408)	(-0.380)	(-0.200)	(0.291)	(.8988)
	FOOT	9.650	-61.270	-10.110	-21.340	-55.070	-26.320	6.050	-6.560	0.987	.5821
		(0.168)	(-1.070)	(-0.176)	(-0.372)	(-0.971)	(-0.460)	(0.106)	(-0.116)	(0.991)	(.5811)
3.*	THIGH	21.788	15.160	22.787	41.930	31.115	32.030	19.514	26.780	0.371	.8538
		(0.348)	(0.265)	(0.398)	(0.732)	(0.542)	(0.484)	(0.340)	(0.468)	(0.357)	(.8618)
	SHANK	37.710	41.000	50.850	60.210	53.540	60.730	68.770	55.330	0.403	.8362
		(0.658)	(0.417)	(0.882)	(1.050)	(0.935)	(1.058)	(1.198)	(0.965)	(0.389)	(.8436)
	FOOT	38.320	49.700	67.790	72.950	71.960	83.670	78.600	64.780	0.413	.8304
		(0.668)	(0.866)	(1.184)	(1.274)	(1.256)	(1.464)	(1.366)	(1.130)	(0.423)	(.8251)
4.*	THIGH	-27.239	-27.466	-21.778	-12.713	-20.397	-15.702	-19.062	-21.036	0.544	.7615
		(-0.475)	(-0.479)	(-0.380)	(-0.223)	(-0.356)	(-0.275)	(-0.333)	(-0.368)	(0.554)	(.7615)
	SHANK	32.910	26.460	16.750	22.550	45.790	14.770	7.480	20.580	0.815	.6825
		(0.574)	(0.462)	(0.292)	(0.394)	(0.764)	(0.258)	(0.130)	(0.359)	(0.872)	(.6215)
	FOOT	30.330	31.770	15.930	43.520	60.790	17.850	6.870	30.130	0.709	.6852
		(0.530)	(0.554)	(0.280)	(0.760)	(1.062)	(0.314)	(0.120)	(0.526)	(0.705)	(.6871)

1. = Touchdown to Takeoff.
2. = Takeoff to Minimum Knee Angle.
3. = Minimum Knee Angle to Maximum Thigh Segment Height.
4. = Maximum Thigh Segment Height to Touchdown.

NOTE: Negative number indicates clockwise movement of segment.
Positive number indicates counter-clockwise movement of segment.

Table F-36

Analysis of
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* 1. = Touchdown to T
2. = Takeoff to Min
3. = Minimum Knee A
4. = Maximum Thigh

Table F-36

Analysis of Gender Effect on Angular Displacement in Degrees (Radians) of Leg Segments for Selected Periods During One Complete Running Cycle for Each Leg.

GENDER LIMB SIDE	MALE R	MALE L	FEMALE R	FEMALE L	F (2,2)	p
1.* THIGH	-51.036 (-0.890)	-46.822 (-0.816)	-53.498 (-0.934)	-43.936 (-0.767)	0.133 (0.124)	.8827 (.8894)
SHANK	-49.722 (-0.868)	-53.098 (-0.912)	-50.745 (-0.886)	-45.502 (-0.794)	3.599 (4.346)	.2174 (.1870)
FOOT	-76.969 (-1.343)	-90.550 (-1.580)	-78.693 (-1.402)	-64.360 (-1.122)	2.847 (2.589)	.2599 (.2787)
2.* THIGH	58.656 (1.008)	49.640 (0.867)	42.588 (0.728)	36.240 (0.633)	4.482 (4.556)	.1824 (.1800)
SHANK	-16.890 (-0.295)	-11.930 (-0.205)	-32.390 (-0.564)	-41.600 (-0.551)	1.882 (0.653)	.3470 (.6049)
FOOT	-3.780 (-0.071)	-21.960 (-0.384)	-20.950 (-0.366)	-35.790 (-0.625)	0.876 (0.867)	.5329 (.5356)
3.* THIGH	20.151 (0.351)	24.960 (0.423)	27.451 (0.463)	32.990 (0.551)	0.934 (0.643)	.5171 (.6088)
SHANK	44.929 (0.781)	51.940 (0.905)	60.504 (1.055)	56.690 (0.989)	1.122 (1.102)	.4713 (.4757)
FOOT	64.090 (1.120)	66.370 (1.160)	64.240 (1.116)	69.180 (1.208)	0.005 (0.004)	.9951 (.9955)
4.* THIGH	-26.297 (-0.458)	-20.601 (-0.360)	-17.942 (-0.314)	-17.858 (-0.312)	1.683 (1.680)	.3727 (.3731)
SHANK	26.030 (0.437)	11.210 (0.195)	25.430 (0.443)	30.970 (0.541)	1.394 (1.495)	.4178 (.4008)
FOOT	19.760 (0.345)	22.320 (0.390)	37.222 (0.651)	39.310 (0.686)	0.652 (0.654)	.6054 (.6047)

* 1. = Touchdown to Takeoff.
2. = Takeoff to Minimum Knee Angle.
3. = Minimum Knee Angle to Maximum Thigh Segment Height.
4. = Maximum Thigh Segment Height to Touchdown.

NOTE: Negative number indicates clockwise movement of segment. Positive number indicates counterclockwise movement of segment.

Table F-37

Analysis for
(cm) of Cente

STAGE LIMB SIDE HEIGHT	F
HUMERUS	30. (3
FOREARM	27. (3

* = Percent of stan

Table F-38

Analysis for G
(cm) Centers o

GENDER LIMB SIDE HEIGHT	
HUMERUS	
FOREARM	

* = Percent of standi

Table F-37

Analysis for Stage Effect on Forward-Backward Swing Linear Displacement (cm) of Centers of Mass of Arm Segments.

STAGE	1		2		3		4			
LIMB SIDE	R	L	R	L	R	L	R	L	F	p
HEIGHT	80.6		93.5		97.6		107		(6,2)	
HUMERUS	30.37 (38)*	53.36 (66)	49.35 (53)	56.23 (60)	57.11 (58)	47.84 (49)	62.77 (59)	68.24 (64)	0.519	.7745
FOREARM	27.10 (34)	54.29 (67)	41.76 (45)	51.10 (55)	45.57 (47)	47.05 (48)	49.00 (46)	57.44 (54)	0.220	.9373

* = Percent of standing height.

Table F-38

Analysis for Gender Effect on Forward-Backward Swing Linear Displacement (cm) Centers of Mass of Arm Segments.

GENDER	MALE		FEMALE			
LIMB SIDE	R	L	R	L	F	p
HEIGHT	96.2		93.2		(2,2)	
HUMERUS	51.945 (54)*	57.460 (60)	47.855 (51)	55.370 (59)	0.088	.9195
FOREARM	43.513 (45)	51.670 (54)	38.201 (41)	53.270 (57)	0.123	.8908

* = Percent of standing height.

Table F-39

Analysis for
in Degrees (R

STAGE LIMB SIDE	R
HUMERUS	-75.550 (1.268)
FOREARM	-15.118 (-0.264)

Note: "-" = clockwise
* Significant for righ

Table F-40

Analysis for G
Displacement i

GENDER LIMB SIDE
HUMERUS
FOREARM

Note: "-" = clockwise ro

Table F-39

Analysis for Stage Effect on Forward-Backward Swing Angular Displacement in Degrees (Radians) of Arms.

STAGE	1		2		3		4		F	p
LIMB SIDE	R	L	R	L	R	L	R	L	(6,2)	
HUMERUS	-75.550 (1.268)	-78.570 (-1.352)	-57.300 (-1.014)	-70.720 (-1.214)	-46.960 (-0.894)	-64.540 (-1.122)	-119.180 (-2.074)	-104.410 (-1.822)	0.343 (0.353)	.8690 (.8639)
FOREARM	-15.118 (-0.264)	-55.840 (-0.976)	-102.370 (-1.786)	0.330 (0.006)	-76.082 (-1.330)	-76.670 (-1.338)	-142.200 (-2.536)	-109.150 (-1.930)	18.273 (14.062)	.0528* (.0679)

Note: "-" = clockwise rotation of limb segment measured from the distal end.
* Significant for right forearm. 1 2 3 4

Table F-40

Analysis for Gender Effect on Forward-Backward Swing Angular Displacement in Degrees (Radians) of Arms.

GENDER	MALE		FEMALE		F	p
LIMB SIDE	R	L	R	L	(2,2)	
HUMERUS	-74.000 (-1.335)	-73.190 (-1.268)	-75.000 (1.290)	-85.930 (1.487)	0.465 (0.595)	.6824 (.6268)
FOREARM	-88.947 (-1.553)	-68.440 (-1.196)	-78.938 (-1.405)	-52.220 (-0.924)	1.234 (0.589)	.4476 (.6293)

Note: "-" = clockwise rotation of limb segment measured from the distal end.

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