A Biomechanical Analysis of Running Variances Due to Physiological Fatigue among Highly Skilled Female Distance Runners

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A BIOENGINEERING ANALYSIS OF RUNNING VARIANCES DUE TO
PHYSIOLOGICAL FATIGUE AMONG HIGHLY SKILLED
FEMALE DISTANCE RUNNERS

by

Alison B. Stanford

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Arts
Department of Health, Physical Education,
and Recreation

Western Michigan University
Kalamazoo, Michigan
August 1986

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A BIOMECHANICAL ANALYSIS OF RUNNING VARIANCES DUE TO PHYSIOLOGICAL FATIGUE AMONG HIGHLY SKILLED FEMALE DISTANCE RUNNERS

Alison B. Stanford, M.A.
Western Michigan University, 1986

The problem of the study was to investigate the effect of physiological fatigue upon mechanical alterations in running. The investigation involved a biomechanical analysis of kinematic parameters which compared running mechanics of subjects both fresh and fatigued.

The study revealed numerous alterations in running mechanics associated with fatigue. Maximum vertical displacement of the body's center of gravity was found during the toe-off phase and was significantly less during fatigue. Stride lengths were found to be as much as 2.72 feet shorter during fatigue and stride times as great as .42 seconds shorter. Extension of the support leg was less and flexion of the recovery leg was greater during fatigue. An optimal 90 degree elbow flexion was markedly changed during fatigue. Lastly, non-support times were determined to be less, and support times were greater during fatigue.
ACKNOWLEDGEMENTS

I wish to thank my committee members, Dr. Mary Dawson, Dr. Roger Zabik, and Dr. Harold Ray for their time in making this thesis possible. I also wish to thank John Gartland for his help and suggestions. Very special thanks go to Dr. Dawson for her time, assistance, and patience. Finally, I wish to thank all those who participated in the study.

Alison B. Stanford
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A BIOMECHANICAL ANALYSIS OF RUNNING VARIANCES DUE TO
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CHAPTER I

INTRODUCTION

The skill of running may very well be phylogenetic during initial development, but for a highly skilled athlete it goes far beyond this initial stage of development. In order for an athlete to experience success with the skill of running on a competitive level, he/she must possess a degree of efficiency in the skill. Efficiency, unlike the skill itself, is not resistant to external environmental influences. Running, just as any other competitive skill or activity, requires practice to attain an optimal level. Efficient performance is the prime objective for individuals involved in endurance type activities.

There are two variables that are used to quantify "efficiency" of running. The first is mechanics, which is best accomplished through photoinstrumentation. The second is physiology, measured through heart rate response, blood lactate accumulation, oxygen consumption, and oxygen utilization. When attempting to develop running efficiency, both mechanically and physiologically, the effect of the fatiguing process must be considered. Fatigue is defined as a decreased capacity or complete inability of an organism to function normally due to excessive stimulation or prolonged exertion. As a result of physiological fatigue during activity, movement will often be impaired or altered, according to the degree of exertion. In the skill of running, fatigue may result from: (a) a diminishing
ability of the body to supply oxygen to the muscles and to remove waste products, (b) a depletion of energy stores in the body, (c) dehydration and/or electrolyte depletion, and (d) lactic acid accumulation in the muscle cells and extracellular fluid. These changes reduce the athlete's muscle power and alter neuromuscular coordination. Muscles that become fatigued change the mechanical movements of the runner, thus altering the pace and efficiency. It is clear that mechanical efficiency, as well as physiological efficiency, are important factors in the over-all outcome of competitive and successful running.

Statement of the Problem

The problem of the study was to investigate the relationship of physiological fatigue and perceived exertion to biomechanical variations in running form when performing at a maximal running effort on a treadmill. The study attempted to:

1. Determine the differences between perceived exertion preceding and subsequent to the onset of fatigue;
2. Determine the changes which occur in segmental joint positions before and after the onset of fatigue;
3. Compare perceived exertion and biomechanical alterations in running form; and
4. Compare physiological fatigue and biomechanical alterations in running form during the span of testing.
Purpose of the Study

The purpose of this study was to determine changes in the mechanics of running in female distance and middle distance runners in a fatigued state. Verification of fatigue was determined by measuring heart rate (HR) and ratings of perceived exertion (RPE). The information from this study was intended to assist coaches in understanding the fatiguing process during distance and middle distance events.

Delimitations

The study was delimited to the following:
1. Five highly skilled female middle distance runners ranging in age from eighteen to twenty-two years;
2. Females who had previous experience with treadmill running;
3. Females who competed in the National Collegiate Athletic Association, Division I classification in cross country and/or track; and
4. Athletes who competed in events ranging from 800 meters to 10,000 meters.

Limitations

The study was limited by the following:
1. Running mechanics may have been altered due to the fact that all subjects were tested on a motor driven treadmill rather than over ground;
2. A small sample size, due to accessibility of subjects; 
3. The fact that fatigue was measured subjectively; and 
4. Subjects were not a random sample.

Need for the Study

Little information exists concerning the effect of fatigue in the movement patterns of female runners. Research has involved males, but for the most part females have been neglected. Due to the vast physiological differences between males and females, it is virtually impossible to perform research on one gender and generalize to the other.

There is also a need for applied research. In order to assist coaches of female track athletes in the area of running, a better understanding of the mechanics of running is essential. Information concerning the mechanics of running during the fatiguing process could provide information useful for coaching.

Assumptions

The following assumptions were made:

1. All subjects were in a fresh state during the first filming (the first thirty seconds of the test);
2. The procedure of cinematography provided an accurate account of the activity with minimal distortion;
3. The body segmental endpoints were digitized from the film with consistency;
4. Mechanical alterations were assumed to be due to fatigue and not to the inexperience of treadmill running; and
5. Data were representative of highly skilled female runners.

Hypotheses

The following hypotheses were formulated based on the review of the literature and the results anticipated from the study:

1. Stride length decreased and stride frequency increased due to the fatiguing process.
2. In the fatigued state, the time spent in the support phase increases while the time spent in the flight phase decreases.
3. Running mechanics become significantly altered as the runner reaches a fatigued state.
4. There is a relationship between alterations in running form due to physiological fatigue and a high perceived exertion.

Definition of Terms

1. Anaerobic Threshold—the starting point for lactic acid accumulation. Also, anaerobic threshold is referred to as metabolic acidosis.
2. Angle of Body Lean—the angle between the horizontal plane and a line extended from the greater trochanter of the femur to the tragus of the ear.
3. Borg Perceived Exertion Scale—an instrument designed to measure the intensity of physical work and effort using a rating scale.
4. **Center of Gravity**—an imaginary point representing the center of weight distribution for an object: that point in the body about which the entire weight of the body may be considered to be concentrated; and that point about which all other parts are in balance with each other.

5. **Driving Phase**—that part of the running stride when the supporting leg projects the body into flight or an airborne phase.

6. **Flight Distance**—the horizontal distance that a runner's center of gravity travels while airborne.

7. **Flight Phase**—the part of the running stride when neither foot is in contact with the ground.

8. **Horizontal Forces**—forces which are equal and opposite reactions that tend to accelerate a runner forward.

9. **Knees Even**—the time when the knees are in direct alignment with each other when viewed from a sagittal plane.

10. **Landing Distance**—the horizontal distance that the toe of a runner's lead foot is forward of the center of gravity at the instant of landing.

11. **Maximum Heart Rate**—the greatest number of times the heart can beat during one minute of intense exercise. Maximum heart rate was mathematically calculated by subtracting the age of the subject from 220.

12. **Mid-Stance**—that point during the support phase where the greater trochanter of the supporting leg is in direct alignment with the foot of the supporting leg.
13. Perceived Exertion—a subjective rating of an individual's work intensity during exercise, by the individual.


15. Sagittal Plane—the longitudinal vertical plane dividing the body into right and left halves.

16. Steady State—a balance between supply and demand of oxygen during exercise. The oxygen transport system is able to supply adequate amounts of oxygen to the working tissue so that heart rate, ventilation, and oxygen consumption can be maintained at a constant level for indefinite periods of time.

17. Stride—one complete cycle of running which begins with right foot plant and ends with the next right foot plant.

18. Stride Frequency—the number of strides that a runner takes in a given amount of time.

19. Stride Length—the sum of the take-off distance, the flight distance, and the landing distance during one complete stride.

20. Stride Time—the time it takes to complete one stride.

21. Supporting Leg—the leg which is in contact with the ground during a running stride.

22. Supporting Phase—that portion of the running stride which begins when the foot lands and ends when the center of gravity passes over the foot.

23. Take-Off Distance—the horizontal distance that the body's center of gravity is forward of the toe of the take-off foot at the instant the foot leaves the ground.
24. **Transverse Axis**—the axis that divides the body horizontally into a top half and a bottom half.

25. **Vertical Displacement**—the distance which a body is moved in an up and down motion.
CHAPTER II

REVIEW OF LITERATURE

The review of literature pertinent to this study is divided into four main areas: (a) physiological foundations of running and fatigue, (b) the biomechanics of running, (c) running mechanics and fatigue, and (d) perceived exertion.

Physiological Foundations of Running and Fatigue

Physiological fatigue is defined, by Sparks (1975), as a decrease in work capacity by the act of performing work. It is caused by physical or muscular work and is a severe limitation in sustaining work. Fatigue as the result of hard running at maximal effort involves respiration, circulation, and neuromuscular function. Ventilation increases as a result of more oxygen needed by the muscles and tissues to compensate for energy expenditure. Also, external respiration increases because of a result of large gradients for gaseous diffusion. Carbon dioxide must be taken out of the body and replaced by oxygen. As a result, ventilation not only increases in terms of breaths per minute, but it also becomes deeper to increase alveolar ventilation. When a runner is running in an aerobic state, fatigue occurs very slowly because the energy supply is equal to or greater than the energy demand. Fatigue occurs more quickly when the intensity of running increases and the aerobic system is not able to keep up with the energy demands. As a result, an oxygen debt
accumulates. When this happens, energy must be supplied anaerobically (Sparks, 1975). The anaerobic system comprises two energy generating processes used to meet intensified energy demands. The first anaerobic process relies on the formation of a substance called adenosine triphosphate (ATP). This is accomplished by the anabolism of ATP from phosphocreatine (PC) and adenosine diphosphate (ADP), a product of the utilization of ATP in muscular contraction. This is an anaerobic process because it supplies ATP to the body without the use of oxygen. The supply of PC is depleted in a muscle within a time span of 30 seconds or less. This process is only useful for short bursts of intense muscle activity.

The other anaerobic process is glycolysis. Glucose is catabolized to two molecules of pyruvic acid, and in the process produces ATP for muscular contraction. Again, anaerobic glycolysis, as in the breakdown of PC, does not involve the use of oxygen. If at this time there is no oxygen available, the pyruvic acid will immediately be converted to lactic acid. The build-up of lactic acid in the muscles and the blood contributes to muscle fatigue, especially to a decrease in muscle force and a slowdown in the production of ATP. As a result, anaerobic glycolysis is a useful energy source for only about two minutes of intense activity.

Sparks (1975) did a study involving five world class, male, mile runners. The subjects ran at a four-minute mile pace on a treadmill. Physiological responses during the run were measured each minute and included (a) gas exchange, (b) cardiac stress imposed during the run and (c) blood lactate (collected at the end of the test). The
Subjects were filmed throughout the course of the test. The 16 mm film was digitized and analyzed biomechanically throughout the phases of running. Sparks concluded that running performance depended heavily upon the body's ability to consume and utilize oxygen efficiently. In other words, the more successful performer is able to supply more energy via the aerobic transport system and produce a smaller oxygen debt. Sparks also found in his biomechanical analysis that fatigue causes stride length to shorten and stride frequency to increase. The point at which fatigue occurs largely depends upon the ability and capacity of the runner to tolerate levels of stress placed on the body during intense running.

Karlson and Saltin (1970) completed a study in which several muscle biopsy specimens were taken from three male students. The specimens were analyzed for ATP, CP, glycogen, and lactate. The subjects were tested on a bicycle ergometer set at a workload that produced exhaustion. They found a maximal breakdown of ATP and CP after two minutes of heavy work. Throughout the test, the lactate in the blood increased continuously until exhaustion was reached. It was concluded that the reason for fatigue in the muscles was not the low ATP and CP stores in the muscles, but was the result of a build-up of lactate in the muscle tissue during maximal exercise.

The relationship that exists among variations in running speed and grade and the amount of oxygen required to run at a steady state was investigated by Henson (1976). Six cross country runners from collegiate and amateur ranks served as subjects in the study. Each
of the six ran at combinations of speed and grade (15 combinations) until a steady state was reached. Measurements of oxygen consumption, heart rate, and breathing response were taken once the subject reached a steady state. From his investigation, Henson concluded that the energy costs of running increased in a linear fashion with speed, and that the oxygen consumption per kilometer was constant for running at various speeds, but showed variation with grade. He also found the relationship of heart rate and oxygen intake was linear at sub-maximal workloads.

Astrand (1956) found that oxygen uptake was dependent upon stride length when he measured oxygen uptake at a steady state. He also stated that a stride length which is most natural to the individual will be the most economical, physiologically. The energy cost of running is greatly increased with an increase in stride length. This is why in long distance running it is important to maintain the stride length most comfortable for the individual. The factor of economy and energy efficiency is of great importance. In short distance running like the 100 meter dash, speed is more important than energy economy. For this reason a short distance runner can disregard the energy cost and lengthen his/her stride as much as possible.

Lawson (1975) found in his study of the effect of anaerobic work on different muscle fiber types, that maximal oxygen deficit can be used as a valid indirect indicator of anaerobic energy reserves. He concluded that with this parameter it was possible to quantify the anaerobic capacity of an individual. He also indicated that maximal
oxygen deficit can be estimated accurately and reliably through the performance of a one-minute supra-maximal bicycle ergometer exercise test.

Margaria (1964) did a study involving two champion middle distance runners, where he attempted to assess the efficiency of runners both mechanically and physiologically. He found that the track athletes were five to seven percent more efficient in running mechanics than non-athletic counterparts. He concluded the superior performance of competitive runners was due to their greater capacity and efficiency in the consumption of oxygen, rather than a greater mechanical advantage.

Butts (1982) studied physiological profiles of high school female cross-country runners. She sampled 135 high school cross-country runners who were attending cross-country training camps. The runners ran at zero percent grade at six miles per hour. Every third minute the grade was increased 2.5 percent. The test was terminated at the request of the subject or when objective signs of exhaustion were evident. VO2 max was 49.8 ml/kg/min, with the onset of metabolic acidosis occurring at about 78 percent of this value. A significant correlation (p .01) coefficient of 0.72 was calculated between VO2 max and the onset of metabolic acidosis.

Upton and Hagan (1984) compared physiological characteristics among young and middle-aged female distance runners. Ninety-eight subjects between the ages of 19 and 54 years were used in the study. Subjects age 19 to 29 years comprised the group of young marathoners.
and subjects 30 to 54 served as the middle age category. The ninety-eight subjects were divided into four groups: young marathoners, middle aged marathoners, middle aged 10 kilometer runners, and middle aged sedentary females. All subjects were tested on a motor driven treadmill for maximum heart rate and max. VO2 values. The results showed no significant difference in aerobic capacity between young marathoners and the middle aged marathoners. The VO2 max. of the middle aged marathoners averaged 55.55 ml/kg/min, whereas the sedentary middle aged women averaged approximately 31.4 ml/kg/min. The mean for the young marathoners was approximately 60 ml/kg/min. In conclusion, young and middle aged runners exhibit superior cardiorespiratory characteristics when compared to sedentary middle aged women.

The Biomechanics of Running

In general, the mechanics of running are the same as for walking. Specifically, running is a simpler task than is walking. Babies will often run before they are able to walk. Running differs from walking in that in running there is a period of non-support in which neither foot is in contact with the ground. This is not apparent in walking. The objective of running is to cover the greatest distance in the least amount of time. This can only be accomplished in two ways: (a) by increased stride length and/or the distance covered with each step, or (b) by increased stride cadence (the number of strides taken in a given time). When speaking in terms of stride length, there are three separate distances that must
be summed to give the total stride length (Hay, 1985). They are (a) the takeoff distance, (b) the flight distance, and (c) the landing distance. Leg length will always be a variable in determining the stride length, specifically, the take-off distance. The flight distance will be determined by the speed of the run, the angle that the runner left the ground in the take-off phase, and by air resistance that may be encountered during flight. The most important factor in the flight distance is the speed of release, which is the speed at which the athlete is able to exert a force on the ground in order to project the body through the air. In efficient running form, the landing distance will be the smallest contributor to the actual stride length, as it is only a few inches. Coaches will often tell their athletes to increase this landing distance by kicking forward more with the swinging leg (Hay, 1985). The truth is that by swinging the leg forward, as it lands, it will be too far in front of the center of gravity, thus applying a backward force to the moving body. This slows down both momentum and speed.

The other method of mechanically increasing speed is by increasing the stride frequency (Hay, 1985). A single given stride is the sum of the time the athlete is on the ground and the time the athlete is in the air. Hay (1985) reported the ratios of the contact time and airborne time as (a) 2:1 at the start of a sprint and (b) 1:1.3-1.5 when the athlete is at maximum speed (p. 399). This ratio
is determined by the speed at which the muscles of the supporting leg can project the body forward and upward into the flight phase.

The action of the legs is angular in motion. This angular motion is the result of three phases: (a) supporting phase, (b) driving phase, and (c) recovery phase. The supporting phase begins when the runner's center of gravity passes over the foot. The purpose of this phase is to adjust for the force of impact that the body receives at the foot plant. The impact is a result of gravity, which pulls the body vertically downward, and running speed. The supporting phase also allows the runner an opportunity to get into position for the driving phase. In order for the forces of impact to be tolerated by the body, the hip joint, knee joint, and ankle joint all must flex in order to increase shock absorption for the body.

The driving phase begins when the athlete completes the supporting phase and ends when the contact foot leaves the ground (Hay, 1985). As the end of the supporting phase approaches, the body's center of gravity passes over the support leg, the thigh's backward motion slows down momentarily, as the knee and ankle flex, and the heel touches lightly to the ground. This gives the foot more time in which to apply force against the ground. It also lowers the athlete's body weight, and, therefore, reduces the athlete's moment of inertia, thus making the pivot over the supporting leg faster. The purpose of the driving phase is to push downward and backward against the ground with as much force as possible. This force is brought about by the extension of the hip, knee, and ankle joints. This extension causes the body to be projected forward and upward by
way of Newton's third law of motion. These extensor muscles are very important in that they determine the foot's velocity as it leaves the ground. The velocity at take-off will determine the length of stride. Failure to extend these muscles through their greatest range of motion will result in a decrease in optimal stride length. This is a very common fault of sprinters (Hay, 1985). The driving phase has a vertical component as well as a horizontal (as the result of the downward, backward thrust). In skilled performers, this vertical component equals about two and one-half times the athlete's body weight. This vertical component is important in that it projects the body into the air, thus increasing stride length. Furthermore, if running had only a horizontal component, the force would have a line of action that passed in front of the center of gravity, and the entire body would have angular motion instead of the desired linear motion.

The third phase of the legs in running is referred to as the recovery phase. It is the time in which the non-support leg makes its forward swing in preparation for landing. This rotation is the result of angular motion about the hip joint. During this phase the knee bends sharply and is brought to a position behind the body where the heel is near the buttocks. Formerly, coaches have advocated that this high heel kick up in back was a waste of energy, but now it is seen as being important. The high kick reduces the moment of inertia of the entire limb. This allows for a quicker rotation time about the hip joint. In the recovery phase, the leg after the backswing
will swing forward, led by the knee. The thigh will reach a horizontal position as the lower leg swings forward, and the body makes its downward descent. Knee lift has been researched numerous times, and it has been concluded that a high knee lift is most efficient (Nelson & Gregor, 1973).

The arms play an important role in the running pattern. Because of the muscular connections between the pelvis and the trunk (internal oblique muscles), the opposite and equal reactions of the leg drive are absorbed by the upper body. As a result, the upper body must twist rhythmically in opposition to the leg motion. When the left knee is brought forward in the recovery phase, the hips are rotated in a clockwise direction. Likewise, when the right knee is in its recovery phase, the hips will be rotating in a clockwise direction. Likewise, when the knee is in its recovery phase, the hips will be rotating in a counter clockwise direction about the longitudinal axis. The hip rotation ceases as the knee reaches its highest point in front of the body. The rotation of the hips is what will cause the opposite reaction of the athlete's upper body. The arms move about a sagittal plane, that is, a backward, forward plane. As the athlete's left knee is swung forward and upward, the right arm moves in a forward and upward direction, and the left arm moves backward and downward. The purpose behind this movement is to balance the leg action. The action is reversed when the right knee is brought forward. The arms work with each other. During the forward swing, the arms are held in a flexed position at approximately a 90 degree angle. The arms are swung backwards,
forwards, and slightly inward about the axis through the shoulders. Also, a slight cross-body swing of the lower arm is both natural and desirable. The forward limit of the arm swing is at approximately shoulder level and the backward limit is equal or a little behind the hip. During this backward thrust of the arm, the corresponding shoulder is driven slightly forward. At this point the elbow is straight and the motion gives increased leverage to the driving leg on the opposite side. Toward the end of the arm's backward motion, it speeds up and regains its flexed position (90 degrees), thus matching the final fast stages of the drive leg on the opposite side. The range of arm movement, as represented by the path of its (arm's) center of gravity, is about the same in front of the shoulder axis as it is behind the axis. The arms most definitely speed up the horizontal component of the legs. The arms also add a vertical component to the motion by way of both arms accelerating upward and downward simultaneously. This in turn promotes a downward retardation, thus giving an upward acceleration and a vertical component to the drive. The downward acceleration coincides with the forces between the foot of the supporting leg and the ground. Therefore, the downward acceleration of the arms lessens the impact between the ground and front foot. This is most effective when the arms are carried close to the trunk. In conclusion, the arms may be accelerated either upward or downward at the appropriate time in order to increase or decrease the force between the ground and the supporting leg.
There are numerous reactions which act upon the runner which in essence produce motion. The athlete also exerts numerous forces, thus producing forward motion. The runner exerts a vertical and a horizontal force on the ground during both the drive phase and the support phase of each stride. The vertical component is the resultant of the runner applying force downward during the driving phase. This vertical reaction tends to accelerate the runner upward and rotate her forward about a transverse axis. The horizontal component is the result of the force applied by the driving foot which is in a backward motion. This force will accelerate the runner forward and rotate her backward about the transverse axis. Another force which is external to the body but does not act upon the runner is air resistance. Air resistance will rotate the runner backward about the transverse axis. The extent of the forward motion will depend upon which sum of forces are greater, the backward or braking force. It is at this point that trunk lean comes into play. The position of the trunk in running depends on the position of the runner's center of gravity and the length of the moment arms. When the athlete is first accelerating, the trunk inclination will be greatest in magnitude. When the runner reaches top speed for a certain distance, horizontal forces against the ground will be reduced; thus, the magnitude of trunk lean will lessen. This is because the body is not accelerating to the extent that it was to begin the motion, and so a balance has been met between acceleration and air resistance. The backward rotation has been reduced, so the need for the forward lean is no longer necessary. There still exists
a need for a slight trunk inclination because of the horizontal reaction and air resistance. If this does not take place, then the body's center of gravity will be in front, and the driving leg will be unable to produce horizontal forces against the ground. An exaggerated lean either way reduces stride length. The head must be kept in natural alignment with the shoulders.

Biomechanical Research on Running

Changes in Style Over Time

Nelson and Gregor (1973) conducted a longitudinal study involving the biomechanics of distance running. The problem of the study was to measure the biomechanical changes which accompany the improvement of running performance that occurred as a result of an extended training period. Eleven collegiate distance runners were chosen for evaluation in the longitudinal study. Subjects were filmed while running at selected speeds during the fall and spring seasons. The components that were analyzed were (a) stride length, (b) stride frequency, (c) stride time, (d) time of support, and (e) time of non-support. Both individual differences and group differences were found. It was concluded that training for distance running over a long period of time produced meaningful changes in running mechanics of experienced runners.

Ground Versus Treadmill Running

Also of concern to biomechanists are the differences between
running over ground and on a treadmill. Numerous studies have been performed to compare and contrast the two methods. For instance, Elliott and Blanksby (1976) used cinematography to biomechanically analyze individuals in selected overground jogging and running and treadmill jogging and running at equivalent velocities. All subjects were adult males and females who were joggers but not competitive track athletes. No significant differences were found in stride length, stride rate, support time, or non-support time for males or females when jogging. At higher velocities of running, differences were recorded. For both males and females, stride length decreased and stride frequency increased; and the period of non-support was significantly less when running on a treadmill as compared to running overground.

Nelson, Dillman, Lagasse, and Bickett (1972) studied sixteen male members of the Pennsylvania State Track and Cross-Country Teams. They analyzed temporal factors and horizontal and vertical velocities of the center of gravity. It was found that the runner on the treadmill tended to place the foot down further in front of his center of gravity and allowed the moving belt to return the foot beneath him. This tends to increase the time of support and decrease the time of non-support for a specific velocity. The treadmill runner must complete the recovery and touch down phases more rapidly in order to place the foot out ahead of the center of gravity. The work done, based on vertical displacement of the center of gravity, would be greater for overground running than for treadmill running.
McMiken and Daniels (1975) in their investigation on aerobic requirements and maximum aerobic power and their relationship to speed in treadmill and track running, tested numerous trained athletes while running at three different speeds on a treadmill and on an outdoor track. For the track part of the test, he made sure that the air velocity and temperature were similar to that of the lab. The subjects all ran three different speeds with a three minute recovery which allowed the heart rate to return to normal. He concluded that aerobic requirements and maximum aerobic power are valid when determined on the treadmill and applied to track runners.

Comparison of Elite Runners and Average Runners

Cavanagh, Pollock and Landa (1977) studied various aspects of a marathon. He found numerous differences in stride length and stride frequency between "good" and "elite" marathon runners. The "good" runners competed at the college level, whereas the "elite" runners were considered world class. Cavanagh et al. found that elite runners have a shorter, quicker stride than the good runners. Also, a slight difference in ankle motion was found. Good runners push off (flex the ankle) more, and this is the reason behind their longer stride. Elite runners were more symmetrical during their flight phase. The good runners were often asymmetrical, going up higher on the left foot compared to the right foot.

Hoshikawa, Matsui, and Miyashita (1973) analyzed the running pattern of eight adult males. One was considered an elite runner, four were average runners, and two were poor runners. The subjects
were tested on a treadmill at seven different speeds ranging from 200 m/min to 500 m/min. The total stride time of the elite runner was found to be longer than the time of the poor runners at every speed. As the speed was increased, the displacements of the knee and ankle joints became larger, but that of the trunk decreased. The elite runners' displacement was larger than the poor runners' at a given speed. The ankle's range of motion increased with speed, and the elite runner had a much greater range than the other groups.

Running Mechanics and Fatigue

There has not been extensive research involving both parameters of biomechanics and fatigue. The most comprehensive study of this nature was done by Sparks (1975), who measured both physiological and biomechanical parameters of fatigue. Others studied mechanical parameters measured at the beginning of a maximal effort and at the end. Fatigue was assumed to have set in at the end of the exercise.

Sparks (1975) studied five world class milers running a four-minute mile on a treadmill. Based on actual quantitative physiological measures, fatigue was able to be defined during the run. Cinematography was used to analyze the body mechanically during the actual state of fatigue. Sparks (1975) observed several interesting happenings. He found that fatigue brought on a shorter stride time. During the first minute of the run, over 50 percent of the stride time was spent in the flight phase. During the last minute, 50 percent was spent in the support phase of the stride. He
observed that when fatigue set in, stride length shortened while stride frequency had to increase due to the constant speed set on the treadmill. The degree of loss of extension of the lower leg was found to be due to lactic acid accumulation as the subject with the greatest decrease in extension had the greatest amount of blood lactate as well. Foot contact was observed to be flat-footed during the last minute while all runners were running on the balls of their feet during the first three minutes of the test. From all that he observed, Sparks (1975) made the following conclusions: fatigue caused the stride length to shorten and stride frequency to increase; and the time when fatigue occurred depended upon the ability and capacity of the runner to tolerate levels of stress.

Haven (1977) studied 17 highly skilled female runners from the United States and Canada, most of whom were members of their country's 1972 Olympic Team. The problem of the study was to describe and compare selected mechanical characteristics of running patterns exhibited by these 17 runners under two conditions. The first condition was assumed to be a condition of non-fatigue. Data for this condition were collected early in the race. The second condition was defined as fatigue. Data for this condition were collected 32 meters before the end of the race. The running pattern was filmed and analyzed using biomechanical instrumentation. Haven found stride length to decrease about 1.3 feet from the beginning of the race (Condition 1) to the end of the race (Condition 2). Mean stride frequency decreased from 1.80 strides per second for Condition 1 to 1.72 strides per second for Condition 2. She
concluded that there were few real changes in the angular positions of the legs and trunk for the different phases of the stride as the race progressed from beginning to end. She also concluded that the relationship between the times of support and non-support within a stride may be an indicator of a fatigued running pattern. The mean time of the non-support phase decreased from 52.70 percent for Condition 1 to 47.06 percent for Condition 2. This was expressed as a percentage of total stride time. Also, the support phase increased from 23.64 percent to 26.46 percent from Condition 1 to Condition 2.

Adrian and Kreighbaum (1973) studied the changes in running mechanics due to fatigue in 13 male Olympians during a 24-hour marathon relay. Each subject ran 27 to 31 miles in one mile intervals. Average mile times ranged from 4:42.13 to 5:10.7 minutes. The runners were filmed from a frontal view at 64 frames per second. The investigators found that as the runners became fatigued, their lateral head motion and shoulder rotation increased, there was a greater deviation in foot placements, and there were differences in leg torques due to changes in foot, leg, and thigh angles from the vertical.

Ehrhart (1957) studied the mechanics as the result of fatigue in three runners each running a mile. The athletes were analyzed at four different times during their mile, which ranged from 4:27 to 4:28 minutes. Erhart reported that stride length decreased throughout the race until the "kick", when it increased to its longest length during the run. The average velocity decreased and
then increased in the final interval. One of the subjects had the
greatest velocity during the final interval, whereas the other three
subjects' velocities were greatest during the first interval.

Bates and Haven (1974) studied the mechanical characteristics
due to fatigue of highly skilled runners during an international
competition in a 4 x 400 yard relay event. Eleven subjects were
filmed at a rate of 100 frames per second at points approximately 185
yards and 405 yards from the start of the race. Bates and Haven
found that the mean stride length and frequency decreased with
fatigue. The average velocity dropped by approximately two feet per
second from the non-fatigued to the assumed fatigued state. The
decrease in velocity was greater for the non-support phase than for
the support phase. In the non-fatigued condition the percentage of
non-support time was greater than the percentage of support time,
while in the fatigued running the percentage of support time was
greatest. The recovery time of the legs was about equal in both
conditions. Percent of stride time for foot descent, foot strike,
and midsupport increased while percent of stride time for take-off,
follow through, and forward swing decreased with fatigue. It was
concluded that these changes in temporal parameters resulted in a
less propulsive stride.

Perceived Exertion

The perceived exertion rating scale is a method used to estimate
or measure physical effort and intensity during exercise. This scale
has extensive application although it does not provide absolute
values in a physical or mathematical sense. The perceived exertion scales which exist provide rough mathematical descriptions of subjects' subjective interpretation of physical effort (Borg, 1977).

The most popular scale used to measure perceived exertion has been the Borg Scale (Borg, 1977). First developed by Gunnar Borg in 1962 (Borg, 1977), the Borg Scale is a very well known instrument used to test the perceived exertion during dynamic work. The initial scale consisted of 21 points but was revised by Borg in 1970 (Borg, 1977) to a 15 point scale. Experiments employing this scale have indicated close correlations between ratings of perceived exertion (RPE) and heart rate or other measures of physiological strain. Borg also found a close correlation between RPE and workload (stress).

There is a difference between stress and strain. Stress is the result of a physical load and is measured in watts or mkp/sec. Strain is the result of a physiological load and is measured by such aspects as heart rate, blood lactate, or other physiological indicators (Ulmer, Lanz, & Lollgen, 1975).

Frankenhaeuser, Post, Nordheden, and Sjoeburg (1969) studied physiological and subjective reactions to different physical workloads. The aim of the study was to measure the catecholamine output brought about by various physical workloads and to relate these measures to ratings of the subjective effort experienced during the work periods. It was noted that assessment of catecholamines in the urine in previous studies was found to be a reliable and sensitive index of sympathetic and adreno-medullary activity. Ten
healthy males served as subjects in the study. The experiment included a control condition and five successive six minute tests of either 150, 450, or 750 kpm/min on a bicycle ergometer. Catecholamine excretion, cardiovascular functions, and subjective effort were studied. Heart rate, systolic blood pressure, and subjective effort were all found to increase consistently with the increasing workload. The Borg Scale was utilized to rate and determine subjective effort.

Docktor and Sharkey (1971) experimented with physiological and subjective reactions to exercise and training. Five healthy, but non-athletic males, served as subjects. They were tested and then trained for five weeks, three days per week. Training involved walking on a treadmill at a speed of 3.5 miles per hour with a one percent grade increase per minute. This proceeded until a heart rate of 180 bpm was achieved. Subjective effort was measured using the Borg Perceived Exertion Scale. Subjective ratings were taken when the heart rate reached 150 bpm. Catecholamine excretion was measured three hours after the session was completed. It was determined that perceptual ratings for the 150 bpm heart rate were similar as the workload increased.

Pandolf, Cafarelli, Noble, and Metz (1972) researched perceptual responses during prolonged exercise. The problem of the study was to determine if cardiac frequency is a factor in the rating of perceived exertion. Ten healthy and fit males participated in the study. Exposure to heat and exercise were used to manipulate heart rate. Cardiac frequency and respiratory and temperature variables were
measured. A multivariate analysis showed that the rating of perceived exertion tended to follow alterations in workload when an increment of more than 200 to 300 kpm/min was implemented. Heat was not found to be a significant factor in perceived exertion ratings. The subjects were able to partial out thermal sensations from the rating of perceived exertion.

Morgan (1973) conducted a series of experiments involving the interaction of perceived exertion, selected psychological states and traits, and metabolic responsivity to tests on a bicycle ergometer. Morgan reported results agreed with other studies of this type. The findings indicated that normal subjects are very reliable in their perception of work intensity using the Borg Psychophysical Category Scale. Although this was a highly subjective method for measuring work intensities, the results mirrored the actual metabolic cost of work performed. Inaccurate measures, however, do occur when the subject is neurotic, anxious, or depressed. Extroverts were found to under-rate work intensity at heavier loads than introverts. All three types of individuals are unreliable in their perception of work performed.

Ulmer and Lollgen (1975) studied ten athletes from sports which train for endurance. The test included four fixed strain values based on a physical work capacity of 170 bpm. Heart rate and perceived exertion were both monitored. The test ceased when a heart rate of 170 beats per minute was reached. Each of the workloads was performed for exactly one minute. The results of the study indicated
that a close correlation existed between RPE-scores to the parameter of strain (heart rate) as well as the parameter of stress (workload). The statistical analysis demonstrated that perceived exertion is considerably more dependent on stress than on strain.

Morgan and Borg (1976) studied the perception of effort in the prescription of physical activity. Thirty males, representing a wide fitness range, participated in the study. The purpose of the study was to evaluate the comparative efficiency of heart rate and perceived exertion to prediction of maximal work capacity. The instruments used in the study were the revised Borg Scale and the bicycle ergometer. The subjects cycled at 60 revolutions per minute (RPM) and at 50 watts for a period of four minutes, after which the workload was increased by 50 watts. The procedure was continued until the subject could no longer maintain the 60 RPM's. Both heart rate and perceived exertion were found to increase in a linear fashion as work intensity increased. It was concluded that the use of a psychophysical category scale, like the Borg Scale, can be effectively used either independently or in addition to the use of heart rate in predicting maximal working capacity.

How one feels at any given time is based upon numerous factors. Burns (1980) stated that whether one feels good or bad at a particular time is governed by either logical or illogical thinking. In other words, the difference between feeling good and feeling bad is a result of what is going on in the mind. The important consideration to be made here, therefore, is not what a person is doing that makes him/her feel bad, but rather, what he/she thinks or
feels he/she is doing. Morgan (1981), studied a 30 year old depressed male who was unable to go to work for two years because he was too weak. He was given a simple dynamometer test. He was found to be substantially stronger than 90 percent of non-depressed, non-hospitalized males. Morgan suggested that the subject was not physically weak, but only thought he was weak. Morgan stated that in exercise and sport, physical performance is not only governed by muscle metabolism but by perception and thought processes as well.

Mihevic, Byrnes and Horvath (1983) completed a review of literature concerning the validity of specific physiological cues in relation to perceived exertion. The review included both local and central factors underlying perceived exertion. Within the literature review, the influence of heart rate on perception of effort has been related, as stated by the majority of studies done in this area. A correlation coefficient of .85 was reported between perceived exertion and heart rate response to a bicycle ergometer task involving progressively increasing exercise intensities. This value was found to be consistent for a treadmill task. Perceived exertion and heart rate were found only to be related across several exercise intensities. This relationship was much less for a single exercise intensity. Research indicates only a .40 correlation for individual exercise intensities. Also, through the review, very little relationship was found between perceived exertion and respiration or ventilation. The correlations most frequently found were .57 to .78 and .47 to .65 between perceived exertion and ventilation and
perceived exertion and respiration, respectively. The literature suggests that physiological responses to exercise act as a source of perceptual information during exercise but not one of them, on their own, prove to be a primary source of perception. Other physiological factors, local in nature, also have been studied as input factors for perceived exertion. Of these local factors, lactic acid accumulation appears to most closely resemble a primary factor for perceived exertion. Lactate may only, however, influence perceived exertion at high intensity levels of exercise.

A new scale, the category-ratio perceived exertion scale, created by Borg, was used in a study by Noble, Borg, Jacobs, Cici, and Kaiser (1983). The purpose of the investigation was to study the relationship between perceptual ratings from this new category ratio scale and some physiological variables during exercise. To determine this, ten physically active males were administered a progressive maximal exercise test on a bicycle ergometer. Perceived exertion scale readings were related to blood and muscle lactate accumulation and heart rates during the tests. All ratings showed a positively accelerating increase with exercise intensity as did both blood and muscle lactate. Heart rate also increased, but in a linear pattern. It was concluded that the perceptual rating scale was an accurate measure of glycogenolytic metabolism leading to lactate accumulation during exercise.

Burke and Keenan (1984) attempted to determine the energy cost of the elementary backstroke and to investigate whether heart rate and perceived exertion are useful in monitoring exercise intensity.
Five females and five males swam the elementary backstroke at four different intensities. The subjects' VO2 max., heart rate, and perceived exertion were monitored at each of the four intensities. It was found that each of the three dependent variables increased with increasing intensity. There were no significant differences for heart rate or perceived exertion between males and females. The greater weight of the men resulted in a higher VO2 max. at each of the four intensities.
CHAPTER III

EXPERIMENTAL PROCEDURES

The problem of the study was to determine mechanical alterations due to physiological fatigue among five highly skilled female distance runners. Perceived exertion and heart rate response to mechanical alterations, in running form, while running at a maximal effort on a treadmill, were used as measures of fatigue.

In order to achieve the objectives of the study, the following procedures were followed: (a) selection of the subjects, (b) selection of the testing instruments, (c) pilot study, (d) collection of the data, and (e) data analysis.

Selection of Subjects

Subjects were five highly skilled distance runners who competed in track events ranging from 800 meters to 10,000 meter distances. All of the women selected as subjects competed in Collegiate Division I Track. Two of the athletes were Division I, N.C.A.A. qualifiers and one had been a previous Olympic trial qualifier. The subjects were chosen based upon their willingness, accessibility, and their previous running history. All of the women who participated had been running competitively for at least five years. Table 1 describes the five subjects individually and as a group.

All subjects signed a consent form and completed a general running questionnaire which provided information concerning their
running career. See Appendix A and Appendix B for the consent form and the running questionnaire, respectively.

Table 1
Descriptive Statistics of Personal Characteristics for the Sample

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Weight (KG)</th>
<th>Competitive Running Years</th>
<th>Miles Per Week</th>
<th>Height (in)</th>
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<td>63</td>
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<td>53.40</td>
<td>7.2</td>
<td>41</td>
<td>64.8</td>
</tr>
</tbody>
</table>

Instrumentation

The following testing instruments were deemed most appropriate for the study: Borg Perceived Exertion Scale, cinematography, computer, heart rate monitor, Neumonics digitizer, and a treadmill.

Borg Perceived Exertion Scale

The Borg Scale is an instrument implemented in the present study to measure an individual's perception of exercise intensity. In Borg's model of perceived exertion, a score of six corresponds to a very light load where heart rate is average or approximately sixty beats per minute. From the lowest reading of six, the scale
continues up to a reading of twenty which corresponds to a very hard intensity or an average maximum heart rate of 200 beats per minute. Borg devised the following perceived exertion scale using healthy, middle aged, Swedish men on a bicycle ergometer. Borg's intent for the scale was that heart rate (HR) equals the perceived exertion reading (RPE) multiplied by ten; HR = RPE x 10.

Cinematography

Due to the nature of the study, cinematography was employed to observe the differences in running patterns between the subjects prior to and subsequent to the onset of fatigue. From a qualitative standpoint, the most accurate measurements can be obtained from the film in a controlled lab setting. To capture the motion with the greatest degree of accuracy, 400 ASA/ISO film was employed. A 16 mm camera was set at a speed of 100 frames per second. The high speed camera was a Photo-Sonics 1-PL equipped with a 12 x 120 mm zoom lens. The camera was loaded with Extochrome 7250 newsreel film. A shutter angle of 160 and an f-stop of 2.8 were set prior to the filming.

Computer

An Apple II+ computer was utilized in the data analysis process. The computer was interfaced with a Neumonics digitizing system. The computer consisted of a screen, keyboard, disk drive, printer and plotter. The plotter was used in conjunction with software to draw
stick figures from the digitized film data. The computer provided kinematic data for each subject.

**Neumonics System**

The digitizing system implemented in the study was a model 1224 Neumonics System. The X and Y coordinates for each body parameter were determined from the film by the Neumonics System. Also, a reference measure was recorded in order to convert graph units to feet. A round off feature included in the 1224 Model estimated X and Y coordinates to the nearest .0001 unit (feet).

**Treadmill**

The treadmill used in the study was a motor driven Quinton Model 18-60. Both pace and grade were held constant for each subject throughout the test. The speed could be altered from 15 miles per hour, a four minute mile pace, to one mile per hour, a six minute mile pace.

**Pilot Study**

On February 13, 1985, a study similar to the present investigation was conducted. The study measured mechanical alterations due to physiological fatigue in a 35 year old female runner. The subject ran a seven minute and thirty second mile pace for twelve minutes. She discontinued the test when her pulse reached 185 beats per minute. The subject was filmed during the first 15 seconds of the run and again during the final 15 seconds of the run.
when the heart rate reached 185 beats per minute. Numerous mechanical changes were found between the first 15 seconds and the last 15 seconds of the run. It was concluded that measurable degenerative changes occurred in running. The purpose of the pilot study was to test the reliability of the testing instruments and procedures for the present study. Perceived exertion was not measured or used as an instrument in the pilot study.

Collection of the Data

Data collection occurred between the first of July and the seventh of July, 1985. Subjects were tested on different days based upon their availability. The treadmill was positioned perpendicular to the camera's field of view, and 40 feet from the lens. The camera speed was set at 100 frames per second. The lighting in the lab was insufficient for picture clarity so two artificial light banks were utilized for the filming sessions. The light banks were placed at 45 degree angles to the treadmill and to the subject. The background behind the treadmill was a plain black curtain to aid in photographic clarity. Prior to filming the subjects, a reference measure (yardstick) was filmed. The reference measure was essential in establishing a scale value to permit the conversion of graph units to actual distances. When the subjects first entered the lab, they were given a consent form (see Appendix B) to read and sign. Next they were weighed. Subjects were given sufficient time to warm-up before the actual test. The treadmill was set on zero percent grade and a
speed which corresponded to the subject's request. The heart rate monitor was then strapped onto the subject and heart rate was recorded. The subject was then asked to run on the treadmill until a heart rate of 185 beats per minute or a perceived exertion of 19 was reached. Each subject was given emotional support and encouragement by the same person. This aided the subject in remaining on the treadmill for as long as possible.

The subject was first filmed within the first thirty seconds of the treadmill test. Prior to the filming a heart rate was recorded and the Borg Perceived Exertion Scale was held out before the subject. The subject was to point to the number which best represented the subject's total body feeling at that particular moment. Prior to the start of the test, the subject was given the following instructions concerning the Borg Scale:

Your goal is to rate your feelings that are caused by the work and not the work itself. These feelings should be general, that is, about the body as a whole. We will not ask you to specify the feeling but to select a number that most accurately corresponds to your total body feeling. Keep in mind that there are no right and wrong numbers. Use any number you think is appropriate. (Burke & Keenan, 1984, p. 23)

During the first 15 seconds of each minute that the subject remained on the treadmill a heart rate and a perceived exertion measure were recorded. When the subject reached a heart rate response of 185 beats per minute and/or a perceived exertion of 19 on the Borg Scale, a second filming was administered. This concluded the test. Elapsed treadmill time was recorded for each subject at the conclusion of the test.
Data Analysis

The following variables were calculated to be used for the comparison between the two conditions, fresh and fatigued: (a) correlation between time and perceived exertion; (b) correlation between time and heart rate; (c) center of gravity displacement; (d) stride length; (e) knee flexion and extension during the drive phase; (f) elbow flexion during the drive phase; (g) stride time for both conditions, fresh and fatigued; (h) average linear velocity of the lower leg during the recovery phase; (i) time spent in the support phase during one complete stride for both conditions, fresh and fatigued; (j) time spent in the non-support phase during one complete stride for both conditions, fresh and fatigued; and (k) correlation between stride length and stride time for both conditions, fresh and fatigued.
CHAPTER IV

RESULTS AND DISCUSSION

The problem of the study was to investigate relationships between physiological fatigue, perceived exertion, and biomechanical variations in running of elite females performing at maximal speeds. For purposes of clarity this chapter was divided into the following sections: (a) comparison between subject's heart rate, perceived exertion, and time on the treadmill, (b) total body center of gravity, (c) stride length analyses, (d) stride time analyses, (e) changes in joint angles, (f) linear velocity of the lower leg, and (g) temporal analyses of the running stride.

Comparison Between Heart Rate, Perceived Exertion, and Time on the Treadmill

Though each of the five subjects was comparatively of equal abilities, there was considerable variance between the time that each subject was able to remain on the treadmill (refer to Table 2). All the subjects ran at a six minute per mile pace. All but one of the subjects had sharp increases in heart rates during the first thirty seconds of the test. The heart rate followed a pattern that showed a sharp increase at the beginning of the test, then continued to increase at a slower rate for the first two minutes of the testing period. From this point it leveled off as the subject reached a steady state condition. As the subject reached the state of
exhaustion, the heart rate did not necessarily increase. In three cases it declined as the subject approached exhaustion.

Perceived exertion followed a pattern similar to that of heart rate (refer to Table 2). Perceived exertion values, however, did not fluctuate in the same manner as heart rate. In other words, it did not revert to a lesser value after reaching a steady state. At times, perceived exertion figures were repeated, even though the test duration continued to increase. Time on treadmill was better correlated to perceived exertion, $r = .99, .93, .87, .98$ and .98 for Subjects 1, 2, 3, 4 and 5, respectively, than to heart rate, $r = .83, .94, .59, .01$, and .17 for Subjects 1, 2, 3, 4 and 5, respectively. In most instances, as the time increased, so did the perceived exertion values.

Table 2

<table>
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<th>RPE</th>
<th>Subject</th>
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<td>14:00</td>
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<td>12</td>
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<td>14:00</td>
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<td></td>
<td>15:00</td>
<td>186</td>
<td>14</td>
<td></td>
<td>15:00</td>
<td>168</td>
<td>19</td>
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<tr>
<td>5</td>
<td>15:24</td>
<td>174</td>
<td>19</td>
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<td>1:00</td>
<td>179</td>
<td>7</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Smoothness and efficiency of the stride are the mark of an elite runner and are the result of minimal vertical displacement of the body's center of gravity. The center of gravity of all runners in the study followed a wavelike path through the various stages of the running stride. For all subjects, the highest peak the center of gravity reached was during the toe-off phase of the stride, within the driving phase. This was found to be true in both the fresh and fatigued analyses. There was, however, significant discrepancy noted between the actual vertical displacement evident during the toe-off phase fresh, compared to the toe-off phase fatigued, for all subjects. Though the toe-off phase produced the highest vertical displacement in both fresh and fatigued analyses, the toe-off phase during the stride while the subject was fresh, was markedly higher.
than the toe-off phase when the subject was fatigued. It was clear from the results that the fatiguing process produced less vertical displacement of the center of gravity and therefore critically less power during the driving phase. The reason for this decrease in power during the driving phase is due primarily to a decrease in the extension of the foot and ankle joints.

Maximum downward center of gravity displacement was found during the knees even phase of the running stride. This was true for four of the five subjects during both the fresh and fatigued conditions. One subject reached her lowest downward displacement during heel contact when she was fresh and during toe-off when she was fatigued. At the time when the knees are even (midstance), the center of gravity is directly over the base of support. This lowering of the center of mass is due to the decreased angle of the knee joint in the support phase and occurs just before the ankle joint begins to extend in preparation for the driving phase. The center of gravity is lowered as a result of the impact which takes place immediately preceding knees even during foot contact with the ground.

In conclusion, all subjects were found to have minimal vertical displacements during the running stride analyzed. These runners were all relatively smooth and efficient.

Stride Length Analyses

As fatigue set in, stride length shortened for all subjects except Subject 5. Subject 5's stride length remained constant.
Refer to Table 3 for data on stride lengths. The largest difference in stride length, 3.7 ft. between the two conditions, fresh and fatigued, was found for Subject 2. Subject 5 can be considered most efficient, as no change in stride length was determined as a result of fatigue. All other subjects experienced large changes in stride length, ranging from 1.49 to 3.7 ft. from when they were fresh to when they were fatigued. Numerous other investigators have found similar results in relation to changes in stride length due to fatigue. Sparks (1975) stated that the shortening of the stride was due primarily to increased lactic acid production during the last two minutes of the maximal run. Other researchers have indicated that the decrease in stride length is due to an increase in the viscosity of the muscle tissue during fatigue.

Table 3

Stride Lengths for All Subjects Both Fresh and Fatigued

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stride Length Fresh (ft)</th>
<th>Stride Length Fatigued (ft)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.46</td>
<td>11.97</td>
<td>1.49</td>
</tr>
<tr>
<td>2</td>
<td>11.09</td>
<td>7.39</td>
<td>3.7</td>
</tr>
<tr>
<td>3</td>
<td>10.91</td>
<td>9.24</td>
<td>1.67</td>
</tr>
<tr>
<td>4</td>
<td>12.14</td>
<td>9.42</td>
<td>2.72</td>
</tr>
<tr>
<td>5</td>
<td>10.82</td>
<td>10.82</td>
<td>0.00</td>
</tr>
<tr>
<td>Mean</td>
<td>11.68</td>
<td>9.77</td>
<td>1.92</td>
</tr>
<tr>
<td>SD</td>
<td>1.01</td>
<td>1.55</td>
<td>1.244</td>
</tr>
</tbody>
</table>
Stride Time Analyses

Stride times for all subjects were also computed for both fresh and fatigued conditions. Stride times are reported in Table 4. Subject 1 had the longest stride time, 1.5 sec., and also had the longest stride length, 13.46, while fresh. Subject 1 was also the most elite of all the runners in the study. This subject had a small decrease in stride time (.17 sec.) due to fatigue. Subject 5 did not have any decrease in stride time as she maintained a very constant stride pattern throughout the test. Subject 2 had the greatest increase in stride time. This was directly proportional to stride length. All subjects, except for Subject 5, showed a decrease in stride time when fatigued. This was a result of the stride length shortening. It took less time to complete the stride while fatigued than while fresh. The correlation coefficient between stride length and stride time was .99 and .99, for the fresh and fatigued conditions, respectively.

Table 4

Stride Times for All Subjects Both Fresh and Fatigued

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stride Time Fresh (sec)</th>
<th>Stride Time Fatigued (sec)</th>
<th>Difference (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.53</td>
<td>1.36</td>
<td>.17</td>
</tr>
<tr>
<td>2</td>
<td>1.26</td>
<td>.84</td>
<td>.42</td>
</tr>
<tr>
<td>3</td>
<td>1.24</td>
<td>1.05</td>
<td>.19</td>
</tr>
<tr>
<td>4</td>
<td>1.38</td>
<td>1.07</td>
<td>.31</td>
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</tbody>
</table>

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Table 4—Continued

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stride Time Fresh (sec)</th>
<th>Stride Time Fatigued (sec)</th>
<th>Difference (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.23</td>
<td>1.23</td>
<td>.00</td>
</tr>
<tr>
<td>Mean</td>
<td>1.33</td>
<td>1.11</td>
<td>.22</td>
</tr>
<tr>
<td>SD</td>
<td>.11</td>
<td>.18</td>
<td>.14</td>
</tr>
</tbody>
</table>

Changes in Joint Angles

From the literature reviewed, optimal joint angles were noted for different aspects of the running stride. Hay (1985) has reported that optimal angles for the elbow should be held constant at a 90 degree angle throughout the motion of the arms during each stride. In previous studies, optimal back leg extension has been determined to be 180 degrees at the knee joint. Front leg flexion was determined to be most efficient at 90 degrees of flexion about the knee joint.

Upon reviewing the results of the present study (refer to Table 5) Subject 1 can be considered most efficient according to the literature. For knee extension during the Fresh Condition all subjects except Subject 3 were within 10 degrees of an optimal angle for the drive leg, 170°, 175°, 166°, 175°, and 170° for Subjects 1, 2, 3, 4 and 5 respectively. During the Fatigued Condition the angle of knee extension decreased for all subjects, 160°, 168°, 162°, 170° and 168° for Subjects 1, 2, 3, 4 and 5, respectively.

Knee flexion was measured from the left leg as the right leg was
in the toe-off position. All subjects except Subject 3 and 5 had knee flexion angles that corresponded to the 90° stated in the literature as optimal. The angles were 90°, 90°, 115°, 98° and 120° for Subjects 1, 2, 3, 4 and 5, respectively. During the Fatigued Condition knee flexion decreased for all subjects, 108°, 114°, 129°, 121° and 125° for Subjects 1, 2, 3, 4 and 5 respectively.

Hay (1985) reported a 90° angle for the elbow joint throughout the running stride. Subjects 1, 2, 4, and 5 have right arm angles, 88°, 97°, 85°, and 89°, respectively, that deviated ± 10 from Hay's optimal angle. Subject 3 deviated the most with an angle of 66°. Elbow flexion appeared to be different and below the optimal 90° angle for the left arm during the fresh condition, for Subjects 3, 4 and 5, 43°, 58° and 63°, respectively. Subjects 3, 4 and 5 showed large differences between the right and left arms, 23°, 23° and 26°, respectively, for the Fresh Condition. Differences between Subjects 1 and 2 were 0° and 8° respectively.

During the Fatigued Condition all subjects showed a decrease in the degree of flexion for the right arm, 85°, 80°, 48°, 78° and 75° for Subjects 1, 2, 3, 4 and 5, respectively, and for the left arm 51°, 63°, 40°, 43° and 57° for Subjects 1, 2, 3, 4 and 5 respectively. For all subjects, the left arm deviated more than the right arm from the optimal 90° of flexion.

Regardless of the degree of compliance during the fresh condition, all subjects decreased in efficiency (as defined by optimal joint angles) as they fatigued. Subject 1 lost the greatest
amount of efficiency when considering back leg extension. As the subject fatigued, front leg flexion angles became greater which resulted in decreased knee lift. Back leg extension in all cases became less. In other words, these angles were smaller during fatigue which meant that less force was being produced during the driving phase. Elbow joint angles for all subjects became smaller when the subject was filmed fatigued as compared to being filmed while fresh. This meant that as the subject fatigued elbow joint angles became acute, thus bringing the arms up higher toward the shoulders. This often increased tenseness in the upper body.

Table 5

Joint Angle Measurements of Elbow and Knee Flexion and Extension at Toe-Off in the Fresh and Fatigued Conditions

<table>
<thead>
<tr>
<th>Subject</th>
<th>Condition</th>
<th>R. Knee Extension</th>
<th>L. Knee Flexion</th>
<th>R. Elbow Flexion</th>
<th>L. Elbow Flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fresh</td>
<td>170</td>
<td>90</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>1</td>
<td>Fatigued</td>
<td>160</td>
<td>108</td>
<td>85</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>Fresh</td>
<td>175</td>
<td>90</td>
<td>97</td>
<td>89</td>
</tr>
<tr>
<td>2</td>
<td>Fatigued</td>
<td>168</td>
<td>114</td>
<td>80</td>
<td>63</td>
</tr>
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<td>3</td>
<td>Fresh</td>
<td>166</td>
<td>115</td>
<td>66</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td>Fatigued</td>
<td>162</td>
<td>129</td>
<td>48</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Fresh</td>
<td>175</td>
<td>98</td>
<td>85</td>
<td>58</td>
</tr>
<tr>
<td>4</td>
<td>Fatigued</td>
<td>170</td>
<td>121</td>
<td>78</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>Fresh</td>
<td>170</td>
<td>120</td>
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<td>63</td>
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<tr>
<td>5</td>
<td>Fatigued</td>
<td>168</td>
<td>125</td>
<td>75</td>
<td>57</td>
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</tbody>
</table>

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Linear Velocity of the Lower Leg

A mean linear velocity was computed for each of the subjects' lower right leg during the recovery phase of the running stride. This velocity was computed by averaging four velocities during the legs' forward swing or recovery phase.

Subjects 1, 3, 4 and 5 all showed increases in lower leg velocities for the Fatigued Condition. Subjects 1, 3, 4 and 5 decreased in time spent in the non-support phase of the running stride from the Fresh Condition to the Fatigued Condition; therefore, the lower limb velocity would have to increase to maintain the speed of the treadmill. Since the non-support phase decreased in time during the Fatigued Condition, the radius in which the legs rotated increased which meant that more time was necessary for the leg to recover in the Fatigued Condition. Subject 2 showed the only decrease in lower leg velocity from the fresh to the Fatigued Condition. Subject 2 also showed the greatest lower leg velocity, 4.75 fps, in the Fresh Condition while Subjects 1 and 4 had the slowest lower leg velocities, both 2.93 fps, in the Fresh Condition. Subjects 1 and 4 had the longest non-support phases, .33 and .24 second, and were the two tallest subjects (height) in the testing sample. Subject 2 was found to have a short non-support phase, .22 second, and was the shortest (height) of all subjects in the test sample.
Table 6
Average Linear Velocity of the Lower Leg
During the Recovery Phase

<table>
<thead>
<tr>
<th>Subject</th>
<th>Fresh Condition</th>
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<tbody>
<tr>
<td>1</td>
<td>2.93</td>
<td>3.5</td>
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<tr>
<td>2</td>
<td>4.75</td>
<td>3.13</td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
<td>3.01</td>
</tr>
<tr>
<td>4</td>
<td>2.93</td>
<td>4.05</td>
</tr>
<tr>
<td>5</td>
<td>2.8</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Temporal Analyses of the Running Stride

Temporal analyses of three running strides were made, comparing on-ground times while fresh and on-ground times while fatigued. The same procedure was administered in comparing flight time while fresh to flight time while fatigued. Averages were determined for each subject and are presented in Table 7. Each stride was measured from toe-off of the right foot to toe-off of the right foot. For all subjects and for both conditions, fresh and fatigued, the non-support time was less than or equal to the support time. Differences existed within the conditions. From the fresh to the fatigued condition support time increased for Subjects 1, 2, and 5, .33 -.37, .33 -.37, .39 -.44 second, respectively. Subject 3 remained relatively the same for fresh and fatigued conditions. Subject 4's support time decreased significantly between the fresh and fatigued conditions, .41 and .25 second, respectively.

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An opposite pattern was observed in the non-support phase, Subjects 1, 2, and 4 times decreased from the fresh condition to the fatigued condition, .33 - .28, .22 - .18 and .24 - .17 second, respectively. Subjects 2 and 4 remained the same for both conditions, .20 and .19 second, respectively.

According to Sparks (1974), a shorter non-support phase is due to a lack in the ability of a powerful leg thrust needed for a longer flight period and a longer stride. The inability to have this powerful leg thrust could be attributed to an increase in lactic acid production during the fatigued portion of the experiment. There is an increase in oxygen required to sustain work, as a result of lactic acid production. Therefore, there is a change in the viscosity of the contractile elements of the muscle because of the increased waste products during anaerobic metabolism. The change in the contractile elements of the muscle cause the leg thrust to be less, therefore the time of non-support is shortened during fatigue and support time lengthened.

Table 7
Average Support Time Versus Average Flight Time for All Subjects Fresh and Fatigued

<table>
<thead>
<tr>
<th>Subject</th>
<th>Support Time Fresh (sec)</th>
<th>Support Time Fatigued (sec)</th>
<th>Non-Support Time Fresh</th>
<th>Non-Support Time Fatigued</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.33</td>
<td>.37</td>
<td>.33</td>
<td>.28</td>
</tr>
<tr>
<td>2</td>
<td>.33</td>
<td>.37</td>
<td>.22</td>
<td>.18</td>
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</tbody>
</table>

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Table 7—Continued

<table>
<thead>
<tr>
<th>Subject</th>
<th>Support Time Fresh (sec)</th>
<th>Support Time Fatigued (sec)</th>
<th>Non-Support Time Fresh</th>
<th>Non-Support Time Fatigued</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>.35</td>
<td>.36</td>
<td>.20</td>
<td>.20</td>
</tr>
<tr>
<td>4</td>
<td>.41</td>
<td>.25</td>
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<td>.17</td>
</tr>
<tr>
<td>5</td>
<td>.39</td>
<td>.44</td>
<td>.19</td>
<td>.19</td>
</tr>
</tbody>
</table>
CHAPTER V

SUMMARY AND CONCLUSIONS

Problem and Procedure

The problem of the study was to investigate mechanical alterations in running parameters due to physiological fatigue. The subjects were selected based upon their running abilities and their desire to participate in the study. Each subject ran at a constant six minute per mile pace on a treadmill until exhaustion was reached. Exhaustion was defined through the use of heart rate and perceived exertion.

Findings

The study included the following findings:

1. Vertical displacement of the body's center of gravity reaches its highest peak during the toe-off phase.

2. Vertical displacement of the center of gravity at toe-off was markedly decreased during fatigue for all subjects.

3. Maximum downward displacement of the body's center of gravity was during the knees even (midstance) part of the running stride.

4. Shorter event individuals perceived their exertion to be at a greater level sooner than longer distance event individuals.

5. Mean stride length for all subjects while fresh was 11.7 feet.
6. Mean stride length for all subjects fatigued was 9.8 feet.
7. Mean difference in stride length from the fresh to the fatigued condition was 1.92 feet.
8. There were changes in stride lengths and stride times from fresh to the fatigued conditions.
9. Mean stride time while fresh was 1.33 seconds.
10. Mean stride time while fatigued was 1.11 seconds.
11. The mean difference in stride time equaled .22 second.
12. There was a change in the amount of extension of the support leg during the driving phase in the fatigued state.
13. Mean decrease in extension of the take-off leg during the drive phase was 5.6 degrees.
14. Mean decrease in flexion of the lead knee during the drive phase was 16.8 degrees.
15. All elbow joint angles became less than the optimal 90 degrees during the fatigued condition.
16. While fresh, 4 of 5 subjects had elbow joint angles within 10 degrees of the optimal 90 degrees.
17. Maximum deviation in elbow flexion of the right arm from the fresh condition to the fatigued condition was found to be 18 degrees.
18. Maximum deviation in elbow flexion of the left arm from the fresh to the fatigued condition was found to be 36 degrees.
19. Linear velocity of the lower leg is decreased during foot contact with the ground and during mid-flight.
20. Based on Pearson's Correlation Coefficient, perceived exertion was better correlated with time spent on the treadmill than was heart rate.

21. Subjects 1, 3, 4 and 5 all increased their lower leg velocity from the fresh to fatigued condition.

22. All times in the non-support phase either decreased or remained constant from the fresh to the fatigued condition.

Conclusions

Within the limitations of this study, the following conclusions were drawn:

1. There are definite mechanical alterations which take place as a result of the fatiguing process.

2. The changes in vertical displacement may be an indicator of fatigue.

3. Perceived exertion and heart rate are accurate methods of measuring fatigue in elite female runners.

4. The relationship between the times of support and non-support within a stride may be accurate indicators of a fatigued running pattern.

Implementations

The results of this study may be implemented in the following manner:

1. Coaches and runners could use the descriptive findings of this study in order to determine when in a race an individual
performer changes from a normal to a fatigued running pattern.

2. The results of this study can aid in assisting coaches and runners in becoming more mechanically efficient.
APPENDICES
APPENDIX A

SUBJECT DATA SHEET
SUBJECT DATA SHEET

PERSONAL INFORMATION

NAME: ________________________________________

SUBJECT HEIGHT: ______________________________

SUBJECT NUMBER: ______________________________

AGE: ________ YEARS

WEIGHT _________ LBS. = _________ KG.

YEARS YOU HAVE BEEN COMPETITIVELY RUNNING? ________________

HOW MANY MILES PER WEEK DO YOU RUN? ________________ MILES.

WHAT EVENT(S) DO YOU RUN? ____________________________________

TEST RESULTS

HEART RATE PRIOR TO TEST: ________________ BPM.

TREADMILL SPEED: ________________ MPH.

CAMERA SPEED: ________________ FPS.

SHUTTER SPEED: ________________

F-STOP: ________________

TABLE OF TEST DATA

TIME  HEART RATE  PERCEIVED EXERTION

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APPENDIX B

CONSENT FORM
CONSENT FORM

I understand that:

- I will be asked to run on a treadmill for the purpose of determining mechanical changes that occur due to fatigue,
- I will determine the speed of the treadmill and will run until I reach my predicted maximum heart rate or I perceive my exertion to be at a maximal level and cannot continue,
- I have the right to withdraw from the study at anytime,
- all data will be confidential,
- all data will be destroyed after the completion of the study,
- I may request my film or it will be destroyed along with the data,
- someone will spot the back of the treadmill to guard against the risk of falling back off the treadmill,
- the researcher recommends a physician's approval to participate in this study.

SIGNATURE ____________________________________________
DATE ________________________________________________
WITNESS _____________________________________________


