

CHARACTERISTICS OF ELITE FEMALE COLLEGIATE DISTANCE RUNNERS
WITH RESPECT TO SELECTED BIOMECHANICAL AND
PHYSIOLOGICAL FACTORS

CHARACTERISITCS OF ELITE FEMALE COLLEGIATE DISTANCE RUNNERS
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An abstract submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

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Distance running performance is determined by both biomechanical and physiological parameters. In this study, the biomechanical parameters measured were stride length and stride frequency and the physiological parameter measured was maximal oxygen uptake. The purpose of this study was to investigate which of these biomechanical or physiological parameters had the greatest influence on the peak performance of elite collegiate female distance runners. For this study, peak performance was defined as the personal best performance in the mile run. Seven elite collegiate female distance runners completed a specifically designed maximal oxygen uptake treadmill protocol. This protocol started with a ten minute warm-up at 8:00 mile pace and then progressed to 7:00 pace for 3 minutes with the pace dropping 30 seconds per mile every three minutes until three minutes were completed at 5:00 mile pace. After the completion of the 3 minutes at 5:00 pace, the grade of the treadmill increased by 1% every minute until VO₂ max was reached. During the two speeds of 5:30 and 5:00 mile pace, participants were filmed at a shutter speed of 60 frames per second. The filming was performed in the sagittal plane of the participant with a Canon ZR50MC high-speed digital video camera. Selected trials were digitized and analyzed using the PEAK Modus 8.1 software. The variables measured for each participant were maximal oxygen uptake, stride length, stride frequency, mile personal best, weight, leg length, leg length relative to height, stride length relative to height, and stride length relative to leg length. The results of these variables were statistically analyzed using a multiple regression and bivariate correlation. Results of the study showed significant relationships between peak performance and stride length at 5:00 pace as well as stride length relative to height at 5:00 pace. Stride rate at 5:00 pace fell just outside of the significance range at 0.051. The research

hypothesis stating that stride length would be the most important factor in peak performance was supported by the findings in this study.

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DEDICATION

This paper is dedicated to three of the most important people in my life. All three pushed me farther than I ever thought I could go and they each did it in their own special way. To my Mother, Barbara Garrison, who instilled confidence, pride, and a sense of accomplishment in me in a way that no one else could. It is her unwavering confidence in me that I carry everyday and it serves as the pilot light of my desire to achieve at the highest level. To my Father, Fred Garrison, who pushed me to my limits during my childhood and adolescence and allowed me to grow and make mistakes. He has been my most proud and avid supporter and believer in me as a man and I am proud to be his son . To my best friend, Dan Gabor, who inspired me to just be myself and who taught me that being myself was always enough.

I carry your faith, inspiration, confidence and love with me every day and I hope someday I can help others in the ways you have all helped me.

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Title Page

Abstract Approval

Abstract

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Chapter 1

INTRODUCTION

For many years, learning how to run faster over greater distances has been a challenge for coaches, elite athletes, fitness fanatics, and hobby-joggers that have each developed their own different theories on how to improve their race times over various distances. Williams (1985) stated that the identification of proper running mechanics can improve performance of athletes at all levels of competition. According to Hay, (1993) the objective of each athlete in a running event is to cover the given distance in the least possible time. The actual time over the distance is determined by the distance of the run and by the average speed the athlete runs over that distance. He states that the speed an athlete runs is the function of two factors: stride length, the distance covered with each stride taken and the stride rate, the number of strides during a given time period ($1/R$). Hay (1993) describes stride length using three components. Takeoff distance is the horizontal distance that the body's center of gravity is in front of the toe of the takeoff foot at the moment the toe leaves the ground. The flight distance is the horizontal distance that the center of gravity travels while the individual is airborne. Landing distance is the horizontal distance that the toe of the leading foot is in front of the center of gravity at the moment the individual lands. To state the possible solutions in a simplified manner, there are essentially two different ways to biomechanically improve speed over distance: increase stride length or increase stride rate. In the past, research has focused more on either stride characteristics or physiological parameters related to distance running performance. These research studies have investigated the importance of

each of these parameters to performance in a single bout of distance running. There are a number of research articles that address the physiology and others that investigated the biomechanical factors that are valuable to a peak performance over a long distance run. However, little has been done comparing the relative comparisons of the biomechanical and physiological parameters and their relative contributions to a single peak distance running performance of elite collegiate female distance runners. With the increase in opportunities for collegiate female runners due to Title IX, it is important that the literature reflect the increased participation of females in track and field. The first Olympic marathon for women was held in 1984 and since then there should be a large amount of studies dedicated to the uniqueness or similarities of the biomechanics of both male and female distance runners. One of the intentions of this study is to add to the knowledge base regarding the stride characteristics of female collegiate distance runners.

Several investigators have examined running speed and its key components. According to Adelaar (1986), running speed is dependent on five key variables. Stride length, gait technique, muscle capacity, body weight, and running surface all combine to affect running performance. In this review article, the author discusses the mechanics of the phases of the running cycle. Those phases are divided into the stance phase, the float phase and the swing phase. The stance phase comprises approximately 40% of the running cycle while the swing and float phases each account for 30% of the cycle.

As one of the first researchers to investigate the roles of stride length and stride rate on running performance, Hogberg (1952a) found that over short periods of intense running, participants increased their speed primarily through an increase in stride length at the beginning of the exercise bout. During this time, both stride length and stride rate

increased linearly with the increasing speed. At approximately 23 km/hr, the increase in speed takes place as a result of an increase in stride rate. During this time, stride length is still increasing, but not to the extent observed in the stride rate. Similar results were found in a study of two well-trained runners. In trials at different speeds, participants ran at either a freely chosen stride length or a determined stride length and researchers concluded that for the trials of freely chosen stride length, the increase in stride length was directly responsible for an increase in running speed (Knuttgen, 1961).

In a separate study, Hogberg (1952b) used one male participant to investigate the effect of differing stride rates and lengths on energy output. The author found that in this well-trained individual, the most economical stride length was very close to the stride length freely chosen by the individual. An increase in stride length increased energy cost more so than did the decrease in stride length. Given several different ways that an individual can increase stride length, Hogberg believed that the best method was to have the individual engage in a more powerful leg drive to gain this increase. In addition, Hogberg reports that several of the greatest distance runners of all time gained success with high stride rates and relatively short stride lengths in an attempt to improve their running economy.

Since biomechanics and physiology each play significant roles in determining peak performance, running economy, which is measured as the oxygen cost of running at a given velocity, is considered to be a very valuable measurement in the analysis of distance running performance. The biomechanical factor of stride length is considered to be a key contributor to running economy. Some other factors that may contribute to improved running economy are a more acute knee angle during the swing phase, low

movement of the body center of mass, little arm motion, low percentage of body fat, and lightweight but well-cushioned shoes (Anderson, 1996). Since the goal of competitive distance running is to run a specified distance in the least amount of time, efficiency and economy can play key factors in a successful performance (Anderson, 1996). Thus, if stride length is a key component in the increase of running economy, it may also be considered a valuable key to improved performance. Both mechanics and physiology play key roles in the determination of running economy (Daniels, 1985).

Purpose

The purpose of this study was to determine which biomechanical or physiological measurement (stride length, stride rate, or maximal oxygen consumption) influenced peak performance in elite female distance runners.

Research Hypothesis

It is the ambition of each athlete to attain a peak performance that matches the athlete's potential and work performed during training. It is with this ambition to improve that personal records are achieved and performance enhancement occurs. While it is acknowledged that all of these factors are key components of performance, the research hypothesis for this study was that stride length has the highest negative correlation with peak performance from these factors. That is, as stride length gets longer, the faster the personal best mile performance of the participant.

Assumptions

1. All participants are healthy at the time of testing and are considered to be in or near optimal shape.

2. All participants are free from any orthopedic problems which could change or alter their biomechanics during the testing.
3. The use of a treadmill is valid in the gathering of physiological data (McMiken & Daniels, 1976) and participants have become familiarized with its use.
4. All participants provided a peak performance in which their personal best mile run time was achieved during a collegiate race.
5. All participants are engaged in similar training programs with the only deviations coming from individual needs determined by their coaching staff.

Definitions

Maximal Oxygen Uptake: the maximal rate at which an individual can consume oxygen (Brooks, Fahey, White, & Baldwin, 2000). Units used to describe this are measured in milliliters of oxygen per kilogram body weight per minute.

Peak Performance: current mile or 1500 meter personal best time achieved by each participant. Performances over 1500 meters will be converted into mile times.

Stride Length: the horizontal distance between two steps, this includes a period of support and a period of flight. For example, a stride may be measured from the heel of the right foot at the beginning of the cycle to the heel of the right foot at the end of that particular gait cycle (Adrian & Cooper, 1995). It can also be measured from the front of the back foot to the heel of the front foot. Sometimes this is measured as an average over a period of several gait cycles.

Stride Rate: the number of stride cycles during a specified period of time (Buckalew, Barlow, Fischer, & Richards, 1985).

Delimitations

1. All participants are members of the University of Arkansas Track & Field Team.
2. All participants have run a sub 5:04 mile.
3. All participants are female.

Limitations

1. The running mechanics of each individual participant on a motorized treadmill are not exactly the same as each individual participant's mechanics when running on the track, road, or trail.
2. The apparatus worn by each participant during the testing of oxygen uptake may slightly alter running mechanics of each participant. The apparatus consisted of standard headgear with mouthpiece and hose as well as EKG leads with a belt around the waist of the participant.

Significance of the Study

Most of the literature relative to running and running economy has been done on males. This study specifically addresses physiological and biomechanical factors as they influence female elite collegiate distance runners. This population is seriously underrepresented in the current body of research. The rapid rise in numbers of female collegiate distance runners has led to an increasing need to address the specific needs of these athletes. Therefore, if the research hypothesis is supported by the results, it would be recommended that if faced with limited training time, coaches should place a relative high amount of importance on increasing stride length through drills that develop thigh and hip strength and flexibility as well as improved mechanics. It has been shown that short-term audiovisual feedback training can be effective in the optimizing of stride

length in runners with less than economical stride length patterns (Morgan, Martin, Craib, Caruso, Clifton, & Hopewell, 1994). This knowledge could be helpful in the specific training of distance runners and thus add to the ever-growing knowledge base regarding distance runners. Since more women are competing at a higher level now in the United States in the world of collegiate distance running this increase in numbers can only lead to improved performances on the national, world and Olympic levels of competition. In the world of international level distance running, success is measured as winning and failure is often defined as losing. This can be a brutal reality when the difference between the two can be measured in hundredths of a second. This is just one reason that economical performance is crucial to the success of the elite female distance runner.

As a result of their physiological profile of elite female distance runners, Wilmore and Brown (1974) suggested that with further training, improved coaching, equipment and facilities as well as a greater emphasis on women in sport, women would continue to improve and close the gap between the genders. In their study of 11 elite female distance runners, Wilmore and Brown (1974) concluded that when compared to their elite male counterparts, the differences between the two groups are partially social-culturally based as opposed to being strictly physiological or biomechanical. There are basic physiological differences between the elite male and female endurance athletes; however as more research is done, the gap between elite male and female distance runners appears to be closing.

It is commonly accepted that no two humans run exactly the same. Running is a skill that must be learned over time and one's predisposition to successful running is partially determined by genetics. The skeletal arrangement determines many of the

mechanical relationships between the muscles, joints, and body segments that must work together in order to move the body in an efficient manner over the distance being covered during the course of a run. Proper coaching and training can be utilized to improve many postural and technique-related issues but very little can be done to alter the genetic gifts that each individual inherits (James & Brubaker, 1973). Thus, any educational tools that can be developed in order to help coaches should be welcomed into the knowledge base of literature.

Chapter 2

REVIEW OF LITERATURE

In this review of literature, it is acknowledged that biomechanical factors stride rate and stride length and the physiological factor of maximal oxygen uptake all can have significant input into every distance running performance. These factors are important regardless of the gender, experience, fitness, desire, and physical gift of each individual runner. The body of research regarding stride length and stride rate are presented first and is followed by an extensive review of relevant literature which addressed maximal oxygen uptake and its importance in the performance of distance runners. Special attention was paid to any studies that specifically addressed stride or maximal oxygen uptake in the female distance runner. Several cases investigated both the mechanical and physiological parameters and their importance to performance and these studies are placed in the section of the review in which this author deemed to be primary factor that drove the research in each study. Therefore, this review of literature is divided into the following sections: (1) Overview of Stride Length Research, (2) Overview of Stride Rate Research, (3) Overview of Studies using PEAK Modus, (4) Overview of Maximal Oxygen Uptake and Running Studies.

Overview of Stride Length Research

In the late 1960's and throughout the 1970's, East German researchers believed that since walking and running were learned early in childhood, that elite performances in distance running were developed on that early foundation. Pace over all distances is fundamentally determined by the relationship between stride length and stride frequency. The East Germans believed that the eventual development, maintenance, and

improvement of speed over any running event depended on finding the optimal relationship between stride length and stride frequency. Through research, the East Germans developed a table for dependence of running speed based upon stride length and stride frequency. Extrapolating the information in the table shows the stride frequency decreases as distance run increases, stride length and/or frequency can determine the level of performance, and as stride length increased, there must be an improvement in the pushoff during the support phase. This would correlate to an increase in the float phase of the running cycle. The most intriguing extrapolation from the table was the belief that stride frequency was predetermined by heredity, and training had minimal influence on this parameter, thus stating that improvements in performance come about with an increase in stride length (Scholich, 1978).

It is generally accepted that there is such a thing as an “optimal stride length” that at each given speed, each individual uses a stride length that minimizes the metabolic energy used while running. This belief implies that any other stride length, shorter or longer, will inflict more metabolic energy cost on the runner. This stride length only has a moderate correlation with physical height (Cavanagh, 1987). It should be noted that the cost of running is primarily determined by the time the foot is in contact with the ground as well as the cost of supporting the individual’s body weight (Kram & Taylor, 1990). It is with this knowledge that the investigation of biomechanical factors involved with running performance begins.

It appears logical to believe that the taller athlete would have longer legs and thus, run with a longer stride. To carry the logic even further, one might believe that if a tall runner and a short runner are running the same speed, the taller runner would possess a

longer stride length and slower rate when compared to the shorter runner. In a study looking at 37 male sprinters, Hoffmann (1971) looked for the best relationship between stride length and stride rate relative to the individual's leg length. All trials were filmed but no specifics were provided regarding this process. The height and leg lengths were measured using the Martin anthropometer and the Trochanterion. The stride components of stride length and stride frequency were measured during competition. Maximum stride length was averaged during the first four steps from the starting line and the average stride length and number of strides were calculated from the film of the event. Time of the competition was observed with stopwatches and the average stride frequency was calculated by dividing the actual number of strides taken during the race by the time taken to run the race. There was a correction made for the final step heading into the finish line. Hoffmann (1971) found that leg length was more connected to running ability than was actual height. They also found that the stride rates were not significantly different except for several "willowy-type sprinters" with weaker flexor muscles. Hoffmann (1971) surmised that stride lengths among these sprinters did not change from race to race. However, according to Hoffmann, (1971) the sprinter's best race of the season will generate the highest stride rate relative to their other performances (Hoffmann, 1971).

Weyand, Sternlight, Bellizzi, & Wright, (2000) researched sprint mechanics and speed by taking a different turn with the addition of ground forces added as a variable used to reach top speeds during treadmill running. Twenty four men and nine women participated in a study in which they ran on a level treadmill at sub-maximal to maximal speeds while attached to a chest harness. Forces applied to the running surface were

measured using a treadmill-mounted force platform. The variables of stride times, swing times, contact times and airtime were determined by the vertical force signals and averaged over a time period of eight consecutive steps. Results showed that speed increases were generally achieved by an increase in stride length at lower speeds while the speed increases at higher speeds were associated with increasing stride frequencies. The increases in stride frequencies were achieved by reductions in both contact time and swing time. Researchers also found less airtime, or time where neither foot sustained contact with the running surface, as participants' reached top speed. The mass-specific forces applied to the running surface were also found to be significantly greater for the participants who reached the highest speeds. Faster runners applied greater forces during their decreased amount of contact time with the running surface. Conversely, slower runners applied lesser forces during their longer contact times with the running surface. The faster runners were also found to have both longer and more frequent strides compared to the slower runners. Weyand, Sternlight, Bellizzi, & Wright, (2000) concluded that top speeds were reached not by changing stride mechanics but by applying greater forces to the running surface during the contact phase of the stride cycle.

In a study by Shields, (1982) stride length relative to leg length was used as a research parameter and researchers evaluated the relationships between different stride lengths and sub-maximal running performance on a treadmill. Participants were 18 male and 18 female volunteers with ages ranging from 21 to 40 years of age. The mean age of the participants was reported as 28.33 years for men and 26.16 years for women. Each participant was tested at the same time of day on the same day of the week over the course of four consecutive weeks. Participants were provided with one practice session

in order to allow them to become familiar with the treadmill. The treadmill used was a Quinton constant-speed motor driven treadmill set at a speed of 3.39 miles per hour. Individual measurements taken were height, weight, and leg length measured from the top of the iliac crest to the sole of the shoe worn over the course of the study. Stride frequency was kept constant with the use of a Franz electronic metronome. Treatment one had participants use their natural stride length, treatment two used a stride length equal to 60% of participant's leg length, treatments three and four used 70% and 80% of participant's leg length, respectively. Shields (1982) concluded that the average natural stride length is equal to approximately 71.89% of total leg length. Use of this natural stride produced significantly better performance times compared to the 60% treatment group. However, the 80% treatment group produced significantly better results compared to the natural stride treatment and the 60% treatment. These results support the use of a longer than natural stride can be utilized to improve running performance at sub-maximal levels (Shields, 1982).

The notion that individuals develop an optimal stride length which minimizes energy expenditure and improves running economy was studied by Cavanagh and Williams (1982) by using ten male runners and altering their chosen stride lengths while running trials on a treadmill. Each participant ran a 7 minute per mile pace (3.83 meters per second) for 30 minutes on five successive days. The researchers measured each runner's freely selected stride length as a percentage of leg length and had participants alter their stride length over a range of $\pm 20\%$ of leg length. During each of these trials, researchers gathered oxygen uptake information to see if the alterations in stride length had any effects on oxygen uptake at this slightly moderate pace. Researchers found that

trained runners were likely to run at a combination of stride length and stride rate which is extremely close to the theoretical optimal condition. It was believed that each runner, over time, found certain combinations of stride length and stride rate that fit best with their individual running style. The researchers found no strong relationships between stride length and oxygen uptake or stride length and leg length. They also believed that stride length was not a critical determinant of oxygen uptake (used to measure physiological efficiency) in well-trained runners.

In a similar study, Ragsdale (1977) studied the altering of stride length and its effect on heart rate, oxygen uptake and ventilatory responses. Fourteen male participants of varying physical condition ran three bouts on a treadmill for a mile at a 7:30 pace. The stride parameters used for the bouts were natural stride length as well as $\pm 15\%$ of natural stride length. The mile run with a longer stride produced higher heart rates, oxygen uptake, and mean minute ventilation compared to the data gathered during the mile run at natural stride length. The mile run with a shorter stride length also produced higher heart rates, slightly higher yet not significantly higher oxygen uptake, and higher mean minute ventilation. This research confirms that in a relatively active male population, the naturally chosen stride length is more physiologically economical than stride length $\pm 15\%$ longer or shorter than that naturally chosen stride length.

In a very similar study, Powers, Hopkins, and Ragsdale (1982) used three sub-maximal running bouts with varying stride lengths and oxygen uptake measurements to measure the relationship between stride length and oxygen uptake. Twelve trained female runners participated in three sub-maximal running bouts at natural stride length as well as $\pm 15\%$ of their natural stride length. Oxygen uptake was measured during each

of the bouts. Researchers found higher mean heart rates during the short stride trials compared to the normal or longer stride trials. Oxygen consumption was significantly lower for all subjects when running at their natural stride compared to the longer and shorter stride scenarios. The oxygen uptakes during the altered stride trials were not significantly different. Researchers concluded that female runners require less energy to run at their freely chosen stride length and that this could lead to a more economical method of running at a submaximal level (Powers, Hopkins, Ragsdale, 1982).

In a comparison between elite level male and female distance runners, Williams, Cavanagh, and Ziff (1987) filmed fourteen elite female distance runners as they ran on a treadmill until exhaustion at a speed of 5.36 meters per second. Anthropometric measurements were obtained from both the left and right sides of the body using “standard” measurement techniques. Kinematic data were gathered using a 200 Hz NAC video camera and the image and space coordinates were gathered using a Motion Analysis Expertvision system. Four stride cycles were analyzed to determine the positions of laterally placed markers placed on the greater trochanter, knee joint, lateral malleolus, heel of shoe and the head of the fifth metatarsal. These data were then compared to data gathered by different researchers as part of a different study. The comparison showed that the females raised the thigh significantly higher leading to greater angular velocities in both flexion and extension at the hip. Females showed relatively longer stride lengths when compared to leg length as well as stature. Stride length correlated $r=.43$ with stature for the females. Stride length also correlated with a greater change in vertical velocity ($r=.60$). Longer stride lengths also showed strong correlations with increased hip extension ($r=-.63$) and more knee extension ($r=-.56$).

These elite females were also found to be shorter in stature, weighed less, and had shorter legs when compared to the general female population. When compared to the elite male runners running at the same speed, the females ran with more hip flexion, higher angular velocities in hip extension and flexion, and longer stride lengths relative to their leg lengths (Williams, Cavanagh, & Ziff, 1987).

This relationship between running economy, performance and mechanics was studied using 31 trained males who could maintain a running pace of 3.57 m/s (approximately 7:30 mile pace). Researchers gathered physiological and biomechanical data and compared it to previously recorded 10 kilometer run performance. The study confirmed a complex interdependence between metabolic and mechanical variables that contribute to distance running performance. Researchers believed there was no single variable like stride length or maximal aerobic power that were solely responsible for increases or decreases in running economy. In fact they related the relationship to a “weighted sum of the influence of many variables” (Williams & Cavanagh, 1987).

Eleven years later, Lake and Cavanagh (1996) revisited this concept and tested the variable of training as a means to improve running economy. Two groups of subjects were used (one non-active control, one training group) to test if training enhanced running economy. Data collection was performed using high speed film, gas analysis, and a Quinton 18-60 motorized treadmill. After a 5 minute warm-up at 3.08 meters per second, participants ran at the given test speed for 2 minutes to establish the stride pattern. Following the establishment of this stride pattern, participants were then filmed in the sagittal plane for twelve stride cycles at a film speed of 50 frames per second. A Locam 16-mm camera was used and the film was analyzed using a Microgrid II

digitizing tablet (Summagraphics, Inc.). The joint markers used in the analysis were the neck, greater trochanter, lateral femoral epicondyle, lateral malleolus, and two points on the shoe chosen to approximate the location of the posterior margin of the calcaneus and the head of the fifth metatarsal. Stride length was determined as the average of the 12 filmed running cycles. Physiological enhancements were found in the training relative to the control group. The training group significantly increased their maximal oxygen uptake and improved running performance while the control group did the opposite over the same period of time. These results follow established principles of training. However, researchers also found no changes in stride length and other biomechanical measurements in both groups either pre-or post training. This infers that mechanics do not deteriorate following periods of no training.

Mechanics are also not altered significantly in running bouts following one high intensity effort. Researchers supported this claim by studying the biomechanics of ten well-trained male runners. The mean age of group was 33.3 years old, mean body mass was 66.2 kilograms, and mean height was 1.76 meters. The average time for a recently completed 10 kilometer race was 33:45 minutes. Each participant performed several submaximal runs, a high intensity run (90% VO_2max for 30 minutes), and followed this with several more sub-maximal runs. Filming during the final minute of each running trial, 15 seconds of the trial were filmed using standard videography procedures with a sampling rate of 60 Hz in order to gather gait variables. Participants were filmed in the sagittal plane and a PEAK two-dimensional motion analysis system was used to digitize the endpoints of the segments. A stride cycle began and ended at the point of left heel contact. Twenty-one anatomical landmarks were used to determine a fourteen segment

model of the body. Gait factors analyzed were stance phase, step length, step length as a percentage of leg length, shank angle at heel strike, plantar flexion at toe-off, mean trunk angle during stride cycle, and maximal knee flexion during stance. In the runs that followed the maximal run, there was no significant difference in running economy or gait mechanics between the pre and post running bouts (Morgan, Strohmeyer, Daniels, Beaudoin, Craib, Borden, Greer, & Burleson, 1996).

Biomechanical and physiological profiles following a 30 minute maximal treadmill run were evaluated for four days following the maximal treadmill effort. Sixteen male distance runners participated in this study which provided evidence that biomechanical and physiological factors like stride length and running economy were not impaired nor altered significantly in the four days following a maximal effort. The mean age, mass, weekly running mileage and VO₂ max were 30.5 years, 76.5 kilograms, 26 miles, and 59.0 ml/kg/min. respectively. A modified version of the Pate et al. protocol was used as a maximal test. During the economy runs following the maximal test, participants were filmed during the final 30 seconds of the run using a 16-mm Locam camera filming at 100 frames per second in the sagittal plane of movement. The video was then analyzed using a GRAF/PEN Model GP-3 digitizer connected to an IBM computer. This set-up was used to locate the endpoints that comprised a thirteen segment model of the body. Some of the endpoints used were locations on the toe, the head of the fifth metatarsal, a point slightly anterior to the heel, as well as estimates of the heel, ankle, knee, hip, wrist, elbow, and shoulder joint centers, the third metacarpal, the inferior aspect of the ear, as well as the top of the head. Two complete stride cycles were analyzed for gathering kinematic data. Stride time, swing time, absolute and relative step

length and shank angle at heel strike were among the kinematic variables measured. Running economy and mechanics were found to be relatively unchanged during the recovery and submaximal runs that followed the maximal effort (Morgan, Martin, Baldini, & Krahenbuhl, 1990).

The use of optimal stride length drove several groups in the direction of researching the daily variation of step length in trained male distance runners. In one particular study, the mean age of the runners was 34.2 years and their mean 10,000 meter race time was 42 minutes. Researchers studied the step length variability in nine male runners over a course of four weeks. The participants ran on a treadmill at submaximal speeds 5 days a week for a total of 20 sessions. Step length was determined during the final 2 minutes of each run in which voltage changes in the treadmill tachometer were caused by each foot strike and sensed by an amplifier and converted into digital pulses. The step lengths were determined using a treadmill-computer interface by deriving step times as the interval between the digital pulses. Step time values were averaged to calculate the mean step times and then multiplied by the velocity of the treadmill to obtain mean step length. Researchers determined that there is very little variation in step lengths on a daily basis (Craib, Caruso, Clifton, Burleson, Mitchell, & Morgan, 1994). This is contrary to the results found by Kram, Cavanagh and Kerns (1985) when they studied the daily variations in stride length of twelve well trained recreational runners familiar with treadmill running. The brief fluctuations in treadmill belt speed caused by each foot strike allowed the step times to be calculated electronically. The mean step times were measured during the last 2 minutes of each of the five treadmill speeds and then converted into stride length. Results showed daily stride length variations ranging

from 2.6 cm to 2.9 cm. and they concluded that daily variations in running economy are due to reasons other than the variations in stride length.

The measurement of intra-individual step variability was addressed by Belli, Lacour, Komi, Candau, & Denis, (1995) in a study using 29 healthy males with a mean age of 29.2 years. Participants ran on a treadmill at 60%, 80%, 100% and 140% of their maximal aerobic velocity in successive bouts. Stride parameters measured were vertical displacement of the body and step time. Vertical displacement was measured with a kinematic arm made of four light bars linked together with three joints. Researchers used trigonometry, the bar lengths, and angles to determine the vertical displacement. Step time was measured as the space between two consecutive treadmill contacts. Researchers concluded that to obtain accurate stride data, future researchers should observe at least 32-64 consecutive step or 15-20 seconds of running (Belli, Lacour, Komi, Candau, & Denis, 1995).

The effects of varying stride length during running were studied by Williams and Ziff (1991). These researchers investigated whether the variation of eighteen centimeters of subjects' stride length would make any significant alterations to rear-foot motion and running mechanics. Eight male, experienced runners ran on a treadmill at three separate stride lengths and were filmed during their trials. Filming was done with a LOCAM camera with high speed film at a speed of 200 frames per second. After filming, the data were processed and then digitized and smoothed with a 15-Hz digital filter. There were three stride lengths used, one freely chosen stride length that was assumed to be the subjects' natural stride with the additional trials were performed at chosen stride plus ten percent of leg length (long) and chosen stride minus ten percent of leg length (short).

Williams and Ziff (1991) attached an accelerometer to the treadmill which produced an output to signal each foot contact. This helped in the accurate measurement of the stride length data during the trials. Results of the trials showed that as stride length changed, other factors like stride width, rear-foot pronation, and shoulder rotation changed in order to accommodate for the alteration in stride length. The researchers concluded that runners attempt to maintain many aspects of their natural running form even if there are major alterations to other aspects of their natural gait. This conclusion lends credence to the importance of stride length as a critical factor toward efficient and effective form during distance running.

The freely chosen stride length and stride rate at four different treadmill velocities was studied using 10 male and 10 female physical education students from the University of Western Australia. In this study participants ran at 2.5 m/s, 3.5 m/s, 4.5 m/s and 5.5 m/s while being filmed using a Photosonics 16mm movie camera. Stride length was calculated as the sum of the support and non-support phases and then multiplied by the speed of the treadmill belt. Stride rate was the reciprocal of the sum of the two phases averaged over four consecutive strides. Results showed linear increased in both stride length and stride rate as speed increased for both males and females. Results also showed a significant correlation between female stride length and height at all four speeds with a slightly weaker, yet significant, relationship also being seen in the males. It was concluded that in order to reduce risk of injury, novice runners should focus on running at their natural stride length instead of altering it to fit into another persons running rhythm. It was determined that running with a heel strike with a greater horizontal distance for the

support foot in front of the center of gravity could increase the retarding effect on the runner, thus leading to possible injury (Elliott, & Blanksby, 1979).

The stride variables involved in running on different terrains was studied by using a group of nine female club-level runners running over three selected running surfaces. All of the trials were filmed on video using a Sony TR2000 camera recording at 50 Hz in a sagittal plane as the participants ran over a surfaced footpath, short grass, and long grass. Participants ran at a near constant speed of 4.31 meters per second with the pacing help of a cyclist riding along side participants. Two consecutive steps were digitized in order to determine stride length. Researchers found no significant difference in stride cycle time between the groups and the surfaces. There was a significant decrease in running velocity accompanying the increasing difficulty of the terrain. There were no significant differences in step rate while step length increased significantly with each increase in terrain difficulty. These results led researchers to conclude that the female runners altered their velocity and their stride length significantly in response to the increasing difficulty of the terrain which they were running upon (Creagh, Reilly, & Lees, 1998).

The use of stride length as part of a biomechanical profiling system of distance runners was addressed by Cavanagh, Andrew, Kram, Rodgers, Sanderson, & Hennig (1985). In this profile, the researchers used treadmill running trials of two male Olympic distance runners following the 1984 Olympic Games in Los Angeles, California. The participants were filmed with one sagittal and two rear view 16mm high speed cameras. In the sagittal view, the data were collected at 150 frames per second while one of the rear cameras used a speed of 400 frames per second and the wide rear view used 100 frames per second. These speeds were chosen to enhance the ease of analysis for the different

parameters being filmed with each camera view. The stride length data were collected by using stride rate data during a maximal run to exhaustion on a treadmill. The stride rate was measured electronically during the entire run by the detection of the minor changes in belt speed that took place each time there was a footstrike on the treadmill. Average stride length was calculated as the average stride length for each minute of the trial run to exhaustion. During the early part of the run trial, researchers found that the average stride length of Subject A was 110% of his height and the stride length of Subject B was 100% of his height. During the trial, the stride length of Subject A remained the same until the final minute, during that time, his stride length shortened by 6 centimeters. This is very different than the results of Subject B, whose stride length actually increased by 8 centimeters over the period of the trial. Cavanagh et al.(1985) stated that the results of Subject B followed the findings of other studies done on high level recreational runners that show a progressive increase in stride length as fatigue increases.

Gazeau, Koralsztein, and Billat (1997) used 11 sub-elite male distance runners to look at stride length changes during a run to exhaustion at maximum aerobic speed. They used a run protocol on a treadmill with 0% grade at the lowest speed that could be used to elicit maximal oxygen uptake in the participants. The initial running speed was 12 km/h and the speed increased at 2 km/h increments every 3 minutes until the participant reached the pace of their personal best 3,000 meter mark. After this pace, the increments were 1 km/h until exhaustion. Each trial was filmed and the film was then digitized in order to obtain the kinematic data. The trials were filmed in the right sagittal plane at 200 Hz with an NAC HSV 400 camera. The points that were marked for digitizing were the neck, hip, knee, ankle, and fifth metatarsal. Values for stride lengths were calculated as

the mean for six consecutive strides. Results showed that stride length significantly increased from the onset of the test to the midpoint while it did not change significantly from the midpoint to completion (Gazeau, Koralsztein, & Billat, 1997).

These results agree with the relationships found between step length, step rate, and running velocity in a review article by Vaughan (1984). Step length increased in a linear manner until participants reached a velocity of approximately 7 meters per second. This increase in step length matched with mild increases in step rate gradually at lower velocities. However, at velocities between 8 and 10 meters per second, the slope of the relationship curve was much steeper.

The changes in running form during a treadmill run to exhaustion were studied on two groups of fast and slow male recreational runners. In this study, Siler and Martin (1991) hoped to address any biomechanical differences that may come about as a result of a higher fitness level. Biomechanical data were collected using the Waterloo Spatial Analysis Recording Technique (WATSMART) while the physiological data were obtained on a treadmill during a VO2 max protocol. The points that were marked for coordinate data collection were the head of the fifth metatarsal of the left foot, lateral aspect of the left heel, lateral malleolus, center of left knee joint, left hip, left glenohumoral joint, left elbow, and left wrist. The trials were filmed at a speed of 100 Hz for three seconds, thus capturing three strides. Kinematic variables that were calculated from the trials were stride length, peak flexion and extension at the ankle, as well as the range of motion of each of the lower body joints. Baseline data were obtained during the first five minutes of the trial. A final fatigue run was performed at the end of the study in order to gather performance data. Results showed that the mean stride lengths of each

group increased as they became more fatigued. Results also showed that along with the increases in stride length, there were also an increase in knee flexion during the swing phase and that there was an increased range of motion for the thigh that was pivotal in the increase of the stride length. Siler and Martin concluded that fitness level did not effect the changes in stride length and that changes in gait patterns varied from individual to individual regardless of fitness level.

In a series of studies designed to investigate which factors effected individual selection of stride length at steady-state running velocities under several different running conditions, Cavanagh and Kram (1989) used twelve well conditioned male runners and had them run at sub-maximal efforts on a treadmill. Some of the factors these researchers studied were height, stride rate and stride length while running at five different sub-maximal velocities. A Quinton 18-60 treadmill was fitted with a photocell output which allowed researchers to precisely measure treadmill velocity and this photocell was then connected to an electronic timing apparatus. When the participant's foot landed on the treadmill with each step, the speed of the treadmill varied and these contact points were then used to derive step times. Stride length was then calculated using step time and the known treadmill velocity. Researchers found that all participants showed a linear relationship between stride length and velocity. There was little change found in stride rate over the five velocities for the twelve participants. In a separate experiment, Cavanagh and Kram (1989) also found there to be very little correlation between leg length and stride length as well as little correlation between height and stride length. However, it should be noted that even though all correlations were small, they were all positive correlations.

In an earlier study of 22 elite and good male distance runners, participants were filmed in the frontal and sagittal planes at 100 frames per second. After warming up on the treadmill for 10 minutes at a pace of 4.47 meters per second (10mph), participants ran on a level treadmill at four prescribed speeds ranging from 4.96 to 6.44 meters per second (11.1-14.4 mph). To aid in filming, body markers were on various segment endpoints that allowed researchers to gather a total of 12 anthropometric measurements. Ten strides were filmed at each running speed. Researchers found that the good distance runners had longer stride lengths than did their elite counterparts while they were running on a treadmill. The elite runners countered this stride length difference by having greater stride rates. The elite runners also spent less time in the swing phase, less time in the flight (float) phase and more time in the support phase. This finding suggests that as an athlete improves, their chosen stride length will decrease (Cavanagh, Pollock, & Landa, 1977).

In a study that compared differing stride lengths and oxygen cost, 16 males were observed during several different running bouts on a treadmill running at a speed of 230 meters per minute at grades of 0% and 4%. All of the participants were well-trained and all had completed a 10 kilometer road race faster than 35 minutes. Participants had mean age of 25.8 years, mean 10 kilometer race time of 32.03 minutes, and mean VO₂ max of 74.0 ml/kg/min. Stride lengths used by each participant were their freely chosen stride length, a stride length of 8% less than freely chosen stride length and a stride length of 8% greater than freely chosen stride length. Stride length was longer on the 0% grade compared to the 4% grade and there was an increase in oxygen cost for the 4% grade trials. The long stride length increased oxygen consumption by 3.8% over the chosen

stride length while the shorter stride length resulted in a 2.1% increase in oxygen consumption (Heinert, Serfass, & Stull, 1988).

The adaptations of training for 15 sessions at a longer than normal stride length was investigated using seven male runners as participants in this research study. The runners trained at a step length of their chosen step length +10% of their leg length. Periodic measures of oxygen uptake and step length were made during the training time. The longer training step length caused significant increases in cycle time. Step length following the training only increased slightly. Researchers determined that long term kinematic adaptations are subtle due to the lack of significant changes seen following the increased step length in training (Williams, Jones, & Snow, 1991). Thus biomechanical factors like stride length can evolve over years of training and are adaptable to a variety of factors that may disrupt the naturally determined gait parameters.

The variations in stride mechanics as a function of differing velocities in elite female distance runners were studied at the United States Olympic Training Center in Squaw Valley, California. Forty-two elite female distance runners with a mean VO₂ max of 62 ml/kg/min were filmed while they were running at four speeds between 3.7 and 7.6 meters per second. Variables measured were relative and absolute stride lengths, stride rates and support and non-support times. Results showed that stride length increases were the primary cause for the increases in velocity at speeds under 5.5 meters per second (Gregor, Rozenek, Brown, & Garhammer, 1979).

Overview of Stride Rate Research

The connection between stride length and stride rate and fatigue associated with distance running was addressed during a factor analysis of 29 kinematic variables. Some of these

variables included joint angles, speed, duration of time spent in the support and nonsupport phases of the running cycle, angular velocities as well as stride length and stride rate. Previously discussed research stated that stride rate typically increased over the course of a maximal treadmill trial. This research was specifically performed in order to help coaches and athletes understand how the distance runner optimizes their gait patterns under conditions of varying fatigue as well as in competitive, non-competitive, and laboratory settings. The male and female subjects tested were filmed performing in competitive and non-competitive scenarios on the track and filmed once on the treadmill. In all trials, the subjects were instructed to give maximal efforts. They were filmed using a high speed camera at a frame speed of 100 frames per second. A LOCAM camera was used and following filming the data were digitized. An accelerometer was used to provide a measure of the stride length for each minute of running performed on the treadmill. Stride rate and length data were obtained during the cinematographic analysis of the track performances. The researchers found there to be an average increase of 3.25 centimeters in stride length from beginning to end of the trials. They also found that the majority of the increase in stride length resulted from an increased time spent in the non-support phase of the gait cycle. Results were found to be similar among all three testing conditions (Williams, Snow, Agruss, 1991). It could be implied by these results that since stride length increased as fatigue increased and speed remained relatively constant, that stride rate decreased as fatigue increased.

Stride rate and stride length can also effect the shock and pounding the body absorbs as a result of distance running. In a study done on ten male recreational runners, researchers altered the stride rates and stride lengths of the runners and measured the

shock attenuation during each of nine running trials. Shock attenuation was defined as the process of absorbing the impact energy and reducing the amplitude of the energy shock wave that is transmitted through the body during each step of distance running. Head and leg accelerations were recorded at 1000Hz over 10 strides by using uniaxial piezoelectric accelerometers and the stride data were obtained via use of the accelerometer attached to the leg. During the testing, participants matched their stride frequency to that set by an electronic metronome. The preferred stride length and stride rate was determined during pre-trial testing and then each subject was instructed to run at the prescribed trial level. The experimental conditions were 1) three separate speeds, preferred stride rate and either their preferred stride length or running at stride lengths $\pm 15\%$ of preferred stride length 2) three separate speeds, preferred stride lengths, and preferred stride rate or running at stride rates $\pm 15\%$ of preferred stride rate and 3) constant speed, with one trial of preferred stride rate and length, one trial of stride rate equaling $+10\%$ of preferred stride rate with a stride length of -10% of preferred stride length, and the final trial having a 10% decrease in preferred stride rate and a 10% increase in stride length. The results showed that shock attenuation changed only with changes to stride length and did not change with the changes in stride rate. The increase in shock attenuation accompanied the increase in stride length (Mercer, Devita, Derrick, & Bates, 2003). This would imply that shock attenuation would couple with the increase in stride length that has been shown to accompany the later stages of fatigue in distance running.

A different research study looked at similar parameters, instead focusing on comparing natural stride length and shock attenuation before and after a maximal graded exercise test on a treadmill. Participants were fitted with accelerometers to record head

and leg accelerations during the running bouts. The leg accelerometer was fitted to the tibia of the right leg and the other accelerometer was fitted on the forehead. Stride frequency was measured as the inverse of the time between consecutive peaks of leg impacts. Stride length was then calculated from the relationships between running speed and stride frequency. Ten strides were analyzed during runs before and after the maximal test and researchers found the stride lengths to be similar for both bouts. However, shock attenuation was 12% lower in the running bouts following the graded test compared to the running bout prior to the test. Researchers concluded there was less shock attenuated after the maximal bout and that there were only minor changes to stride length following the test (Mercer, Bates, Dufek, & Hreljac, 2003).

The effect of varied stride rate on the deceleration of the shank portion of the leg was studied using 10 well-trained male runners. Participants ran on a treadmill at seven minute mile pace as data was collected using an accelerometer attached to the tibia and using high speed film (200 Hz) to gather sagittal plane movement. The stride rate variations were 10% slower than normal, 5% slower than normal, normal, 5% faster than normal and 10% faster than normal. Researchers calculated peak shank deceleration after each exercise bout and significant differences were observed at between all group means except the normal and 5% slower groups. These findings were applied to an analytical model and determined that at the given running speed, the peak impact forces in the knee and ankle joints decreased as stride rate increased (Clarke, Cooper, Hamill, & Clark, 1985).

Stride rate was found to decrease at the end of an exhaustive bout of treadmill running in a study of 11 males who ran at 90% of maximal aerobic power until they

could run no longer. It was hypothesized by the researchers that stride rate may have been altered in an effort to minimize the increase in oxygen consumption as fatigue increased at the end of the exhaustive effort. Researchers called this stride tuning and surmised that the better the stride tuning, the more economical the run effort. All trials took place on an ADAL 3D treadmill that could measure 3D ground reaction forces during the running bouts. Contact and flight phases of the gait cycle were defined as the points where the vertical force was above or below 100 N, respectively (Avogadro, Dolenec, & Belli, 2003). This research supported previous research performed on 15 trained triathletes who ran on a treadmill at their 3,000 meter race pace until exhausted. In this study, researches also found reduced stride rate as fatigue increased. A kinematic arm and an optical encoder were used to measure center of mass movements as well as angles between the segments of the kinematic arm. The displacement of the treadmill belt was measured during the contact phase of the 3,000 meter run trial using a separate optical encoder that was fixed to a wheel mounted on the treadmill belt (Candau, Belli, Millet, Georges, Barbier, & Rouillon, 1998).

Stride frequency also can play a serious role in the running economy of children as well as adults. Unnithan and Eston (1990) studied 10 aerobically fit 9-10 year old boys and compared them to 10 fit young men of ages 18-25 years. All participants ran on a treadmill at a submaximal pace while oxygen demand as well as stride parameters were evaluated. Stride frequencies were determined using a Panasonic camcorder for video analysis. The camera filmed in the sagittal plane and the last 30 seconds of each running segment was filmed. Stride length was determined using the treadmill speed and the stride frequency. The stride lengths of the boys were considerably shorter than their

mature counterparts. The oxygen demand was higher at all speeds for the boys when compared to the men. Since the stride lengths were shorter, the boy's group had greater stride frequency at every running speed. Researchers compared relative oxygen demand per stride and discovered that the value was similar between the groups. This led the researchers to conclude that the increased stride frequency could be one of the causes for the increase in oxygen demand the boys experienced while running at submaximal speeds.

Stride characteristics can also be evaluated for maximal running efforts over shorter distances. Nummela, Stray-Gundersen, and Rusko (1996) studied the stride characteristics of eight male sprinters and six male distance runners over a trial on a treadmill set at constant velocity. The second part of the study looked at stride characteristics of seven fast men, six slow men, and four women during 400 meter time trials on a treadmill as well as on a 400 meter track. Each trial was filmed by video camera at 50 frames per second and shoe inserts attached to a waist transmitter was used to determine ground contact times during each trial. Results showed that the longer stride lengths instead of higher stride rates determined the higher velocities in the fast males during the 400 meter time trial. The results also showed no significant differences in the percentage decrease of stride length or stride rate among the three groups performing the 400 meters. On the treadmill there was a significant difference in stride length between the sprinters and distance runners with the sprinters having a longer stride length (2.08m) compared to the stride length of the distance runners (1.84m).

With so much research done using males as participants, it begs the question: Are there any biomechanical differences between male and female distance runners? This

question was addressed by Nelson, Brooks, and Pike (1977). In one of the first comparisons of its type, this study used 21 elite female distance runners, 14 elite male distance runners, and 10 male runners from Penn State University. Among the elite runners were several Olympians and national record holders. Although the women were significantly shorter than the men on average, the relative leg lengths of the groups were remarkably close. The female runners were also significantly lighter than the men. Runners were filmed at 150 frames per second while running at different velocities over a specific distance on a track. A Vanguard-Bendix film analysis system was used to obtain coordinate data from the filmed trials and then the data was entered into a custom written computer program which determined the variables of stride length, stride rate, time of support, time of nonsupport, and stride time. These variables were calculated for each of the running trials. When running at the same absolute velocities, females were found to have significantly shorter stride lengths and higher stride frequencies when compared to the men. The mean stride length for females was 6.4cm shorter than that for the males. The means stride frequencies for females were 0.14 steps per second faster than the males across all velocities. It was also found that the females had a significantly longer relative stride length than their male counterparts, thus showing that females have two compensatory mechanisms for overcoming a possible disadvantage of being shorter in height.

In a biomechanical profile performed on elite female distance runners, researchers evaluated the gait characteristics of forty elite female marathoners. All the participants were filmed during the 1984 Olympic Trials marathon at four separate camera locations along the course. The cameras were positioned at the 9, 16, 20, and 24 mile marks in the

26.2 mile marathon. The camera speed was set at 100 frames per second. Each participant was filmed for two full stride cycles. A 16-mm LOCAM camera was used with Angenieux zoom lenses. The film was then digitized and analyzed using a Vanguard motion analysis system. Every 5th frame of the series of 65 per two stride cycles was digitized. This study was intended to address changes in gait of these elite performers as the event progressed. Analysis revealed that almost all the participants carried a high and relatively stable stride rate throughout the entire contest. Results also showed that the stride rates of the top 10 and bottom 10 athletes at each filming location were nearly identical. This shows there is almost no difference in stride rate among the athletes. This leaves stride length as a primary factor determining success at this distance. The longest mean stride length was found at mile 9 followed by a slight decrease between miles 9 and 16. However there was 12% decrease between miles 20 and 24. Therefore speed also decreased along this same trend since stride rates remained relatively constant throughout among all the groups. The stride lengths of the top 10 finishers were consistently larger than the last 10 finishers. Researchers concluded that the maintaining stride length during the competition was likely to be the determining factor affecting velocity and the race outcome (Buckalew, Barlow, Fischer, & Richards, 1985).

In much of the biomechanical research performed with the aim of learning more about human performance and distance running, researchers use the motorized treadmill as a means to estimate actual racing performance in a controlled laboratory setting. Several research studies have evaluated the effectiveness of the treadmill as a means to accurately reproduce the same environment and then performance observed when actual

overland running takes place. The first of these studies used sixteen experienced runners and filmed these runners at three different speeds over three different slopes on the treadmill and an enormous ramp built in the laboratory in order to realistically simulate overland running. Another purpose of building the apparatus was to avoid confounding factors like weather and changing outdoor environmental conditions. The platform was built and designed to be able to provide the nearly identical topographic profile found at the university cross country course. Participants were filmed on the overground running trials first with each participant being filmed five separate times. A motor-propelled string was used to set the pace that was to be run by each participant. The right side of each participant was filmed during all trials on the ramp and the treadmill. The camera was placed at a 90 degree angle from the sagittal plane of the participant. A 16mm Hy-Cam camera with Dupont film was used along with a Millimite camera speed calibration device. The camera was placed 11 meters away from the participant for overground trials and 4.6 meters away for treadmill trials. Points marked on the body of each participant were the ear, shoulder, wrist, hip, knee, ankle and sole of the shoe. Film was analyzed using a Vanguard Motion Analyzer and stride rate and stride length were then determined. Results showed longer stride lengths and lower stride rates on the treadmill at higher velocities. Runners tended to show two modifications to gait during this study. First, the runners placed their foot further out in front of the center of gravity, which would lead to a decrease in velocity, and have the belt of the treadmill return the foot underneath the participant. Thus increasing support time but then the runner spends less recovery time in order to get the foot back in front of the center of gravity. Therefore,

there are fewer strides per second at a given velocity on the treadmill compared to running overground (Nelson, Dillman, Lagasse, & Bickett, 1972).

The second cinematographic analysis of overground and treadmill running used both males and females to look at the biomechanical differences. The overground running was performed on a flat 200 meter track while the treadmill running was performed on a motorized treadmill. Participants were filmed running at several different velocities. While on the track, the participants were filmed on one of the two laps and they were not aware of which lap was being filmed. A 16mm Photo-Sonics camera was used for filming with Kodak Tri-X reversal film running at 100 frames per second. The camera was on a tripod perpendicular to the running action 10 meters away from the treadmill and 20 meters away from the action on the track. The film was analyzed by projecting it into a 45 degree mirror onto a horizontal translucent surface with an Analector movie projector. The digitizing was done with a Numonics Desk Top Digitizer. Researchers found that there were no differences for males or females running overground compared to the treadmill at velocities between 3.33 and 4.78 meters per second. But when the speed increased, stride length decreased and stride rate increased when treadmill running was compared to overground running (Elliott & Blanksby, 1976).

In an interesting attempt to create near identical conditions between running outdoors and on a treadmill, researchers attempted to determine the treadmill gradient that most accurately reflected the actual running cost of running outdoors. Nine well-trained male runners completed 6 different running trials. Each trial lasted six minutes and was completed at six different velocities. The velocities ranged from 2.92 m/s to 5.0 m/s and each participant received six minutes in between each run. This protocol was

repeated six times, once outdoors along a level road and once each on the treadmill set at different gradients. Researchers used the gradients 0%, 1%, 2%, and 3%. Oxygen was collected during the final two minutes of each trial. Researchers concluded that for running speeds between 2.92 m/s and 5.0 m/s, the use of a treadmill gradient of 1% over a duration of at least five minutes exerts the same energy cost as the similar running trial outdoors (Jones & Doust, 1996).

In a study looking into the physiological and biomechanical strain of intermittent, high intensity treadmill running, researchers studied elite male middle distance runners using two protocols performed in random order. One protocol consisted of 14 work and rest bouts of 60 seconds each while the second consisted of 7 work and rest bouts of 120 seconds. Variables measured during the protocols were peak oxygen uptake, peak heart rate, and peak blood lactate. Stride length and height of maximal vertical jumps were also measured. Stride length was measured during the final 15 seconds of the exercise bouts and was calculated using the velocity of the treadmill and the duration of time taken to complete 20 strides. All participants also completed a maximal oxygen uptake protocol at the beginning of the study. Results show that the physiological strain found in the 120-second sessions closely resembled the data found during the exhaustion level of the maximal test. It was also found that neither stride length nor maximal vertical jump significantly changed as a result of the intermittent treadmill protocols (Vuorimaa, Vasankari, & Rusko, 2000).

The effects of consistent training over a period of years and biomechanical training was addressed in a longitudinal study done using male collegiate distance runners from Penn State University. Nelson and Gregor (1996) filmed participants

running at several different speeds during the Fall and the Spring with a 16-mm Locam camera positioned 65 feet away from the center of the second lane of the track. The film speed was 160 frames per second for each of the two trials at each of the prescribed running speeds. Joint centers were marked to show segment endpoints while filming. The stride variables measured from the film were stride length, stride rate, stride time, time of support and time of non-support. Researchers noted the top performances each year by each athlete and found that over the course of 3-4 years, that each athlete improved in their chosen event/s. Out of the stride parameters measured, the group results were remarkably similar. Nine of the ten athletes showed significant decreases in stride length, stride times and support times while their stride rates increased over the course of the 3-4 years. Only one participant did not match this pattern and he showed the opposite changes for stride length, stride rate, and stride time. It was noted that no coaching effected the biomechanics of the runners since the coach specifically did not address biomechanical issues with the participants. Researchers concluded that collegiate male distance runners undergo significant changes in their stride variables over the course of their collegiate careers (Nelson & Gregor, 1976).

Overview of Studies using PEAK Motus

The advance in technology has allowed researchers new avenues into gathering data in the realm of biomechanics. One of these newly developed avenues is the software system, PEAK Motus, developed by Peak Performance Technologies in Centennial, Colorado. A handful of studies have already been published using the PEAK Motus system to evaluate running mechanics. Following is an overview of the research findings obtained using the PEAK Motus system.

The topic of leg stiffness and stride frequency was investigated using four male experienced treadmill runners. Researchers wanted to determine the relative importance of any changes in the stiffness of the “leg spring” when participants changed their stride frequency while running at a prescribed speed. Participants ran on a treadmill mounted force platform at a speed of 2.5 meters per second. The participants ran at nine different stride frequencies derived as percentages of their determined preferred stride frequency. One frequency was the preferred frequency, four were below (-5, -11, -18, and -26%) the preferred stride frequency and four were above (+17, +25, +30, and +36%) the preferred stride frequency. The hypothesized reported was that as stride frequency increased, the stiffness of the leg spring would increase. Results showed that the stiffness of the leg spring increased from 7.0 kN/m to 16.3 kN/m from the lowest stride frequency to the highest, thus supporting the hypothesis stating that the leg spring stiffness would increase as stride frequency increased (Farley & Gonzalez, 1996).

The “leg spring” model was then accompanied by the aerobic component of running in a study done using sixteen well-trained male runners. Participants ran on a treadmill at 3.35 meters per second for physiological measurement of aerobic demand while running at the prescribed speed and ran at the same speed on runway while being filmed in the sagittal plane in order to obtain biomechanical measures. The PEAK Motus system was used to digitize the trials performed closest to the prescribed speed of 3.35 meters per second. Data were obtained during the foot contact period of the stride cycle. Researchers determined each runner’s leg length at foot contact using this system. Results showed that greater spring stiffness was associated with lower aerobic demand,

thus a more economical performance at the prescribed running speed (Hise & Martin, 1998).

The influence of heel lift manipulation on sagittal plane running kinematics was studied using eight female distance runners whom all were considered to be “heel strikers”. It was hypothesized by researchers that increases in heel lift of either 7.5mm or 15mm would result in a reduction in Achilles tendon strain. Researchers filmed and analyzed 10 running trials at each of the three running conditions: no heel lift, 7.5mm heel lift and 15mm heel lift. The heel lifts were constructed of EVA, a common midsole material used in running shoes. Kinematic data were collected at the ground contact phase of the gait cycle and a period of approximately 0.1s prior to and following ground contact. Results showed that a small amount of heel lift (7.5mm) had a significant effect on peak ankle dorsi-flexion and a reduction in Achilles tendon strain (Dixon & Kerwin, 1999).

Once again, the topics of leg spring stiffness and running speed were investigated using thirteen runners as participants. These participants ran over a Kistler force plate at five different velocities of 2.5, 3.5, 4.5, 5.5, and 6.5 meters per second with their speed being monitored by two photocells placed 5.13 meters apart from one another with the force plate lying in the middle of the photocells. Participants were also filmed with two high-speed video cameras with joint markers placed on the lateral surfaces of the joints. The trials were analyzed and researchers found that the theoretically calculated length of change in the leg spring model significantly overestimated the actual length change observed in the legs of the participants. The researchers also concluded that at the given

velocities, stiffness at the knee joint influences most of the leg spring stiffness (Arampatzis, Bruggemann, & Metzler, 1999).

The stiffness of the joints during the stance phase of the gait cycle is responsible for accommodating for any surface changes that may disrupt the runner's center of mass during movement. This is valuable because as running surfaces change, the runner must be able to maintain relatively similar ground contact and stride frequency in order to maintain the established running tempo. Researchers attempted to determine exactly how quickly runners could adjust leg stiffness in response to a change in running surface. Leg stiffness was measured during the first step onto a hard surface after running on a soft surface. Six healthy female participants were filmed while running at 3 meters per second on a 17 meter rubber track with force plates mounted in the middle of the track. Results showed that runners adjusted leg stiffness on the first step of a new running surface in order to maintain the path of the center of mass (Ferris, Liang, & Farley, 1999).

The biomechanical factors affecting running economy have long been a topic of investigation. In a study, researchers had 17 young endurance runners run at 12-13 different running speeds while researchers collected respiratory gases and filmed the running bouts. Ground reaction forces were measured with telemetric EMG readings of selected leg muscles. In the different running trials, oxygen consumption and energy expenditure remained linear with running speed. As expected, an increase in EMG activity as energy expenditure increased was found as well. Video analysis was done using the PEAK Modus as the researchers studied the movement of the fifth metatarsal, lateral malleolus, lateral epicondyle of the femur, greater trochanter, and tragus. These

measurements were used to calculate joint movements and power of the participants during the running trials (Kryolainen, Belli, & Komi, 2001).

Foot strike patterns following clearance of an obstacle were investigated by researchers using four male and six female recreational runners. Participants ran at a self-selected pace unobstructed and then over six barriers of different heights (10%, 12.5%, 15%, 17.5%, 20%, and 22.5% of standing height). A Kistler force platform was placed directly behind the obstacle. The PEAK model 2051 was used to interface the data from the force plate with the sampling models into the computer. Results showed there to be a change in heel strike landing to forefoot landing between the 12.5% and 15% obstacle heights (Scholten, Stergiou, Hreljac, Houser, Blanke, & Alberts, 2002).

Overview of Maximal Oxygen Uptake and Running

The third and final performance factor involved in this study is the measurement and value of maximal oxygen uptake (max VO₂). This physiological parameter, max VO₂ has long been considered to be the “gold standard” for aerobic fitness has also been shown to have a direct relationship with distance running performance. A nomogram was developed by Margaria, Aghemo, and Limas (1975) that can convert running performance time over a given distance to aerobic power given as VO₂max. In a study using many different types of endurance athletes, researchers used a modeling technique to analyze the differences in max VO₂ for the different types of endurance athletes. All participants participated in maximal tests on either the motorized running treadmill or on rowing ergometers. The expired air was collected and analyzed by online breath by breath systems. The results showed that heavyweight rowers had the absolute values for VO₂ max and long-distance runners tested the highest when the values were considered

for relative body weight. This study simply showed that long distance runners place a high value on VO₂ max and that this value may be a determinant of elite performances in these distance runners (Nevill, Brown, Godfrey, Johnson, Romer, Stewart, & Winter, 2003). These results are similar to the ones found by Daniels, Yarbrough, and Foster (1978) where researchers suggested that not all of the improvement in running performance can be attributed to changes in maximal oxygen uptake in a study of well-trained male runners. Noakes, Myburgh, and Schall (1990) also confirm that VO₂max is a valuable predictor of performance in marathon and ultra-marathon runners. However, they found VO₂max to be just one of many predictive variables that could be valuable in predicting performance.

Similar relationships were observed in a study using the men's Swedish national track and field team. All participants were grouped according to event type. The groups were 800 meter runners, 800-1500 meter runners, 1500-5000 meter runners, 5000-10000 meter runners, and marathon runners. The physiological characteristics evaluated were lactate threshold at 4 mmol, maximal oxygen uptake, running velocity, and performance capacity. When the groups were compared, significant differences were found for maximal oxygen uptakes. The higher uptakes were higher the longer the main distance of the group with the exception of the marathon runners. They also determined that 95% of the lactate threshold variance could be accounted for by maximal oxygen uptake. This led researchers to conclude that lactate threshold seemed to be a function of the group differences in maximal oxygen uptake (Svendsen & Sjodin, 1984).

The relationship between maximal oxygen uptake and road racing performance was studied using 14 trained female distance runners. Researchers measured body

composition, maximal oxygen uptake, running economy and attempted to find relationships between these measurements and performance in a local 10,000 meter road race that took place prior to the measurements. All of the participants placed among the top 20 women in a field of 300 female entrants. The participants averaged 43.7 minutes over the 10,000 meter course. Researchers found the road race performances were significantly correlated with maximal oxygen uptake but not significantly correlated to body composition or running economy (Conley, Krahenbuhl, Burkett, & Millar, 1981).

Early research done using 36 college women (12 varsity athletes, 10 physical education majors, and 14 inactive) set out to examine the relationships between maximal oxygen uptake, running performance, and body composition. Maximal oxygen uptake was measured using the Balke treadmill test while body composition was determined using hydrostatic weighing. The running performance was measured using the Cooper 12 minute test. Researchers found that while there was no significant correlation between body weight and running performance, there was a correlation between the lean body weight and run performance ($r=.49$) as well as a higher correlation between lean body weight and maximal oxygen uptake ($r=.71$). This research showed there to be a great need to study females of all activity levels when referring to fitness, performance, and body composition (Katch, McArdle, Czula, & Pechar, 1973).

In a study done on elite Kenyan distance runners, researchers analyzed the physiological characteristics of these athletes in order to better understand their dominance in the field of international distance runners. Thirteen men and seven women were evaluated using max VO₂ and velocity at max VO₂ as determinants of performance. Participants ran on a synthetic 400 meter running track while following a

cyclist who was given pace information via a headset. Velocities were checked with a GPS system made by Cosmed. The results showed that performance over a ten kilometer distance was inversely related to the velocity at max VO₂. Researchers concluded that among these elite athletes, max VO₂ was the main factor in determining performance over a ten kilometer distance (Billat, Lepretre, Heugas, Laurence, Salim, & Koralsztein, 2003).

In the late 1960's, Costill (1967) performed extensive tests on the men's cross country team at Courtland State College. Costill took the average of each of the 17 individual's times over a 4.7 mile run course and separated them into two groups. Group A consisted of the nine fastest runners while Group B consisted of the eight slowest runners. Some of the parameters studied were maximal oxygen uptake, body composition, and resting heart rate. Costill compared the group means on all 16 test items and compared them accordingly. He found that the faster runners were significantly lighter and possessed less body fat. It should be noted that the mean heights of the two groups were exactly the same. The mean resting heart rates of the faster group was lower and the maximal oxygen uptakes of the fast group were significantly higher than the slow group. The conclusion was there was a direct relationship between maximal oxygen uptake and distance running performance.

The women's cross country team at Kansas State University participated in a study that measured their maximal oxygen uptake and running economy at the beginning and end of their cross country season. Results showed an increase in maximal oxygen uptake from 53.8 to 58.3 ml/kg/min and very little changes in running economy when comparing the testing at the beginning and end of the season. Researches concluded that

an eight week training program for competitive cross country running produced improvements in maximal oxygen uptake but not in running economy (Wilcox & Bulbulian, 1984).

Maximal oxygen uptake and 440 yard dash time were found to be the parameters with the highest correlation to a one mile run time in 33 adult male distance runners. Relative maximal oxygen uptake had a negative correlation of $r = -.74$ with mile run time and 440 yard dash time had a positive correlation of $r = .78$ with mile run time. The mean age of the participants was 25.4 years and the mean time for the mile run was 5:15.3. The mean maximal oxygen uptake of the participants was 60.4 ml/kg/min and their average weekly mileage was 33.8 miles per week. These results support the relative importance and value of both aerobic and anaerobic strength (Berg & Bell, 1980). Sucec (1979) used a multiple regression analysis to analyze physiological data gathered on 23 male distance runners. The researcher used one mile and two mile run times and compared them to relative fat, maximal oxygen uptake, anaerobic threshold, running efficiency, oxygen debt, and lean body weight as parameters. Performance variability for the mile and two mile runs were 81% and 83% accounted for by the seven physiological variables.

In a similar study using 29 well-conditioned male recreational runners, researchers investigated the relative importance of anaerobic and aerobic functions, body composition, body size and running mechanics on runs at distances of 800, 1500, and 10,000 meters. The participants in this study ran a mean weekly mileage of 42.1 miles per week. Maximal oxygen uptake was obtained using an incremental work test on a treadmill while the anaerobic power and capacity were obtained using the Wingate

bicycle protocol. Stride variables were filmed during 10 of the final 15 meters of a 60 meter sprint and evaluated to determine the stride length and rate. Maximal oxygen uptake had significant correlations with all three running efforts while only stride length had a significant correlation over the 800 meter distance. The results of this study showed that the physiological parameter of maximal oxygen could be the most important variable over a range of running performances for this group of male runners (Brandon & Boileau, 1987).

These same researchers also used 56 well-conditioned male runners to determine the limiting variables over three middle distance runs. The distances chosen for the testing were 800, 1500, and 3000 meters. Once again, maximal oxygen uptake was determined using a treadmill protocol and stride variables were measured in the same manner as the study previously mentioned. The results showed the highest relationship was between maximal oxygen uptake and all three performance runs. Mechanically, stride length was found to be most related to 1500 and 3000 meter performance. This ran contrary to the previous study done by Brandon and Boileau in 1987. Once again, this study showed that maximal oxygen uptake was the most important factor determining 800, 1500, and 3000 meter performance for this group of male runners (Brandon & Boileau, 1992).

Five years following this study, researchers attempted to establish relationships between 3,000 meter run performance and several different physiological variables. Some of the physiological variables studied were running velocity at lactate threshold, maximal oxygen uptake, running economy at three different speeds, and predicted velocity at VO₂ max. Participants were sixteen well-trained distance runners with a

mean age of 22.4 years and mean VO₂ max of 73.3 ml/kg/min. The average time of the 3,000 meter run trials was 9:46. Using a stepwise multiple regression, researchers determined that the only physiological variable that was a valuable predictor of 3,000 meter run performance was velocity at lactate threshold which accounted for 87% of the variability. Neither VO₂ max nor running economy were strongly correlated with the 3,000 meter performance (Grant, Craig, Wilson, & Aitchison, 1997). The results of this study were confirmed in a 1998 study examining prediction of race performance based on a treadmill test. Results from the exhaustive treadmill test protocol performed by 427 participants showed lactate threshold measured at 1.5mmol to be the most valuable predictor of performance for distances from 1500 meters to the marathon (Roecker, Schotte, Niess, Horstmann, & Dickhuth, 1998).

A review article composed by Billat and Koralsztein (1996) directly contradicts the findings by Grant et al. These researchers are proponents of the use of velocity at VO₂max as the main monitor of runners training and performance. They argue that since velocity at VO₂max used both VO₂max and running economy in one term, that it should be the parameter that research should focus on. These researchers also disagree with Grant et al. by stating velocity at VO₂max closely mirrors running performance time by elite middle-distance runner over 3,000 meters.

Physiological parameters of adolescent distance runners were investigated by researchers aiming to examine the relationships among these parameters. Some of the parameters measured were peak VO₂, lactate threshold and running economy. Researchers used the Wingate cycling protocol to test the twenty-three boys and seventeen girls that were the participants in the study. Body composition was determined

with the use of Harpenden skinfold calipers. Heart rate was determined with the use of Polar heart rate monitors. The treadmill protocol had two phases that included continuous and discontinuous running trials. For the girls, it was found that chronological age had a moderate negative relationship with 1500 meter performance. Peak VO₂, velocity at peak VO₂ and mean power determined by the Wingate anaerobic test all had significant negative relationships with 1500 meter race time. Overall, the parameters that were determined to be the best predictors of 800 and 1500 meter run performance were velocity when the blood lactate was measured at 2.5mmol per liter and velocity at peak VO₂ (Almarwaey, Jones, & Tolfrey, 2003). This research supports the importance of the physiological parameter of maximal or peak oxygen uptake relative to distance running performance.

A variety of physiological factors were tested in order to find the most important variables related to running performance in female distance runners. Researchers tested 57 female runners and measured velocity at lactate threshold, oxygen uptake at the lactate threshold, velocity at the onset of blood lactate accumulation, running economy, maximal oxygen uptake, and velocity at VO₂ max. These results were correlated with performance in a 3 kilometer race. They found that velocity at the onset of blood lactate accumulation had the strongest correlation with a 3 kilometer race. The second strongest correlation was found between the run performance and the velocity at lactate threshold. Maximal oxygen uptake was also strongly correlated with the 3 kilometer run performance. The researchers concluded that blood lactate variables can be used to predict performance in female distance runners but point out that if blood sampling is not

available, maximal oxygen uptake and velocity at VO₂ max may be used instead (Yoshida, Udo, Iwai, & Yamaguchi, 1993).

In another look in to the physiological parameters associated with distance running performance and female athletes, researchers used the paces for 5 kilometer, 10 kilometer, and 10 mile runs as a way to evaluate physiological parameters in 13 women with a reasonable fitness level. The running trials were performed on an outdoor 5 kilometer course. The participants ranged in age from 18-33 years, ran a weekly mileage of at least 30 miles per week and had run competitive 10 kilometer times in the range of 37-48 minutes. The researchers used hydrostatic weighing to determine body composition and they used a motorized treadmill for all the running trials. The treadmill speeds were 196, 215, and 241 meters per minute. Expired gases were gathered in meteorological balloons and were then analyzed using the Beckman E-2 oxygen analyzer. Blood was drawn during the first minute following each trial and lactate analysis was done in a Vacutainer with sodium fluoride and with an enzymatic kit. The maximal oxygen uptakes of the participants ranged from 51.7-68.4 ml/kg/min with a mean value of 59.65 ml.kg/min for the group of participants. The results showed that the physiological data obtained from research regarding running economy, lactate thresholds, and oxygen uptakes could be used to accurately predict the actual running performances of the female athletes used in a laboratory setting. More specifically, running speed at 2.0 and 4.0mmol/l plasma lactate and maximal oxygen uptake explained most of the variance in running performance (Fay, Londeree, Lafontaine, & Volek, 1989).

These results are similar to those found in a study of elite and competitive female distance runners. These participants took part in a maximal treadmill test in order to

study the possible physiological differences that separate elite and good distance runners. The elite runners displayed a significantly higher mean VO_2max than the group of good runners. While there were no other significantly different physiological or metabolic responses to maximal exercise between the two groups (Pate, Sparling, Wilson, Cureton, & Miller, 1987).

A similar study was performed on well-trained male distance runners and similar results were found. As in the study done on females, 13 males were tested on a motorized treadmill and physiological parameters like running economy, velocity at VO_2max , and lactate threshold were tested. Metabolic data were collected on a Tektronix 4052 computer in 30 second segments. Expired gases were collected and analyzed with an Applied Electrochemistry S-3A analyzer as well as the Beckman LB-2 analyzer. Researchers also used a Parkinson-Cowan gas meter fitted with a rotary potentiometer to measure inspired ventilation. Results showed there to be a strong relationship between performance over a ten kilometer race distance and velocity at VO_2max in the well trained male volunteers (Morgan, Baldini, Martin, & Kohrt, 1989).

Similar physiological parameters were also studied on high school female cross country runners from the state of Massachusetts. The participants' performance over the five kilometer race distance at the state championships was used as the performance effort prior to entry into the laboratory. In the lab, participants were put through a battery of tests. Body composition was determined using skinfold measurements taken at the triceps, suprailiac, and thigh. During the maximal run test on the motorized treadmill, metabolic measurements were gathered using a Metabolic Measurement Cart. ECG readouts were used to obtain heart rate data and gas analyzers were used on the expired

gases. Maximal oxygen uptakes in this population ranged widely from 42-55 ml/kg/min. Research showed that in this research sample population, velocity at VO₂ max may not be the determinant of running success. It was also surmised that for the nonelite female adolescent distance runner, running economy plays very little role in predicting success at the 5,000 meter distance. However, it may be used to explain some of the variation in the performances seen among this age group of female distance runners (Cunningham, 1990).

In another study done with high school female distance runners, a profile was created using 127 participants. Body composition was determined with hydrostatic weighing 6-10 times until three consistent results were found. A motorized treadmill was used for the run trials. Heart rate recordings were gathered using ECG recordings and gas samples were gathered and analyzed using a Beckman Metabolic Cart. Ratings of perceived exertion were taken using the Borg scale. At the conclusion of data gathering, all the participants participated in a 3 kilometer race in order to provide competitive performance data. The researcher concluded that quality training instead of quantity of training may be more beneficial to the actual performance times associated with distance running. There was a low correlation between work done per week and actual performance. The researcher also concluded that physiological parameters are simply just one of many aspects associated with positive performances (Butts, 1982).

In yet another look into the physiology and performance of high school cross-country runners, researchers investigated the relationship between lactate threshold and running performance. Participants were 11 male and 10 female members of a high school cross-country team. Each athlete participated in a treadmill run trial in which their

VO₂max and lactate threshold were determined. Blood samples were gathered at the end of each exercise stage in the protocol. Lactate threshold was determined as the VO₂ at a lactate level of 4mmol/L. Performances from the cross country racing season were used as the performance measure. Researchers concluded that lactate threshold was important for running performance, but that VO₂max was a better predictor of performance for this sample (Fernhall, Kohrt, Burkett, & Walters, 1996).

In an evaluation of 13 teenage female distance runners done in the mid/late 1970's Burke and Brush (1979) found some interesting results with athletes who had trained for at least two years. The group of these girls had a mean maximal oxygen uptake of 63.24 ml/kg/min and had a mean mile run time of 5:10.5. They also averaged 49.53 miles per week of training. The researchers at that time determined that young champion female distance runners were high in aerobic power, average in height but lighter than normal for their age, had a high component of ectomorphy, had a smaller skeletal framework than normal and were low in subcutaneous fat for their age. These descriptions were provided to aid coaches in the development of young athletes.

There are studies that incorporate a multidisciplinary approach to research into distance running movement and performance. One such paper addressed the need to combine the use of cinematography with the use of work ergometers such as the treadmill. Authors suggested a need to determine optimal set points for biomechanical, physiological, psychological, biochemical, and other factors that are used to quantify human performance. All of these factors play key roles in determining the efficiency and economy of running performance and a multidisciplinary approach could and should be used to bring the study of human performance to a new level (Cavanagh, & Kram, 1985).

Summary of the Literature

In summary, this review of literature shows that stride length, stride frequency and maximal oxygen uptake are valuable components of performance for athletes of both genders and at all competitive levels. This is the one thing that all these researchers agree on. These researcher disagree on the point of which parameter is the most valuable for the attainment of a peak performance. It has been found that an increase in stride length has a positive effect on performance and it has also been found that it does not have a positive effect on performance. The same can be said for stride frequency. The same cannot be said for maximal oxygen uptake because it is considered the “gold standard” for aerobic fitness and performance. The exact importance of maximal oxygen to peak running performance is one of the constant topics of debate in the academic and athletic communities. In this study, all three parameters were used with a hope of adding to the body of literature and possibly finding out how important each of these components are to peak mile run performance.

Chapter 3

METHODS

The purpose of this study was to determine which biomechanical or physiological measurements (stride length, stride rate, or maximal oxygen uptake) influence peak performance in elite female collegiate distance runners. Following a thorough review of the literature, the following is a description of the procedures used to collect and analyze data for this study.

Pilot Study

Prior to data collection, a pilot study was completed in May 2004. During this pilot, the entire testing protocol was completed using a professional female distance runner with a background very similar to the participants in the study. The testing protocol was designed for this particular study and was found to be an effective method of measurement for maximal oxygen uptake. The participant stretched for 5 minutes prior to getting on the treadmill. Warm-up consisted of 10 minutes of running at 8-minute mile pace. Following the warm-up, the speed increased to a 7-minute mile pace for 3 minutes. The speed then increased by 30 seconds per mile every 3 minutes until the pace of 5-minutes per mile was reached. The participant ran for 3 minutes at this pace and the grade remained 0% during this period of the test protocol. Following the 3 minutes at 5-minute mile pace, the grade of the treadmill increased by 1% every minute until VO₂ max was reached. Max VO₂ was reached using this protocol in an effective manner that suited the needs of the research study. The testing bout was also filmed to ensure proper placement of the camera in terms of distance from the treadmill as well as camera height. Fifteen frames of this bout were then digitized twice with a sixty-minute break in

between digitizing in order to test reliability of the researcher in digitizing points on the peak system. A correlation was performed using SPSS and the correlation between T1 and T2 was $r=.988$. During this pilot test, changes were made accordingly in order to best facilitate testing.

Participants

The participants in this study were seven members of a NCAA Division I university women's track & field team which has been perennially ranked in the top 20 in the United States. All had surpassed the standards used to determine elite status. These standards were the running of one mile under 5 minutes and 4 seconds or running 5000 meters under 17 minutes 10 seconds. All participants were between the ages of 19 and 23 years. The training loads of the athletes ranged between 40 and 70 miles per week. All athletes were healthy at the time of testing and free from any orthopedic problems. All were considered to have optimal fitness since they were tested in the championship part and peaking phase of their outdoor track & field season. All participants signed informed consent paperwork explaining the risks and benefits of the procedure prior to testing. This study was approved by the University of Arkansas Institutional Review Board.

Instrumentation

Each participant performed a maximal run test on the Quinton Q65 series 90 treadmill while being filmed in the sagittal plane relative to the running motion using a Canon ZR50MC high-speed digital video camera with a shutter speed set at 1/2000s. After all the testing was completed, the selected trials were digitized and analyzed using the PEAK Modus 8.1 (Englewood, CO.) system in the Human Performance Laboratory at the

University of Arkansas, Fayetteville. The PEAK system allowed for the frame by frame biomechanical analysis of each trial and facilitated the calculations of stride length and stride frequency. The use of this technology was vital in the analysis of the data.

Markers were placed on the lateral side of the body facing the camera. These markers were placed on the fifth metatarsal, the calcaneal tuberosity, the lateral malleolus, and the lateral condyle. All were marked on the right foot, ankle, and knee. Gas analysis was done using the PARO Medics True Max 2400 Metabolic Measurement System. EKG data were gathered on a Quinton Q4500 machine utilizing a 12 lead EKG.

Procedure

The participants followed a protocol designed specifically for this experiment. The participants stretched for 5 minutes prior to getting on the treadmill. Warm-up consisted of 10 minutes of running at 8-minute mile pace. Following the warm-up, the speed increased to a 7-minute mile pace for 3 minutes. The speed then increased by 30 seconds per mile every 3 minutes until the pace of 5-minutes per mile was reached. The participant ran for 3 minutes at this pace and the grade remained 0% during this period of the test protocol. Following the 3 minutes at 5-minute mile pace, the grade of the treadmill increased by 1% every minute until VO₂ max was reached. During the endurance performance test, the researcher obtained a measurement of the participant's maximal oxygen uptake. When the participant reached a velocity approximating five minute mile pace, the trial was filmed 2-3 times for 20 seconds each time in order to gather data regarding the participant's stride rate and stride length. The video trial that was deemed the clearest was used in data analysis. The camera was set on a tripod at a height of 1 meter from the ground at a distance of 3.5 meters away from the center of the

treadmill. These measurements were tested during the pilot test and found to be best for this study.

Measurements & Calculations

Leg length was measured as the distance measured from the ground (participants stood on floor with socks on) to the top of the anterior superior iliac spine and measured in meters. Stride length, defined as the period measured from right heel strike to the following heel strike, was calculated using the information gathered on the digitized film. The film speed used was 60 frames per second and the belt speeds during filming were fixed at a 5:30 mile pace (4.87 meters per second) and 5:00 mile pace (5.36 meters per second). The high speed digitized film was then edited down to three full stride cycles (right heel contact to right heel contact three times) and the number of frames used to complete the three complete stride cycles was then obtained. Calculations for stride length were then performed by multiplying the treadmill belt speed, the film speed and the number of frames for three stride cycles divided by three. These data were then used to calculate the stride rate by multiplying the number of strides per meter by the fixed treadmill belt speed. Stride length relative to leg length was calculated by dividing the stride length by the leg length. Stride length relative to height was calculated by dividing the stride length by height.

Statistical Analysis

The SAS ® (SAS ® Institute, 1994) program was used to analyze all data. A multiple regression and bivariate correlations were used with an alpha level of $p < .05$. Means, standard deviations, ranges, and correlations were calculated to better understand the data.

Chapter 4

RESULTS

Purpose

The purpose of this study was to determine which biomechanical or physiological measurements (stride length, stride rate, or maximal oxygen uptake) influence peak performance in elite female collegiate distance runners.

Research Hypothesis

It is acknowledged that all three factors influence peak performance of distance running and it is the research hypothesis that stride length will have the largest negative correlation with peak running performance. This negative correlation will mean that the longer the stride length, the faster the personal best in the mile run for the participant. In other words, the fastest runners should have the longest stride lengths.

Individual Descriptions

Participant 1 was a 21 year old with a personal best mile time of 4:55.5. Her background was primarily a middle distance runner who has also become an excellent steeplechaser. Both her leg length and height rank second highest amongst this sample population. She also had the second highest VO2 max, the third longest stride length at 5:00 pace and the fourth highest stride rate. Her data can be found in Table 1.

Table 1

Individual/ Group Demographic and Performance Data

Variable	1	2	3	4	5	6	7	Mean	SD
Age	21	20	19	23	21	23	22	21.3	1.50
Weight	55.88	54.98	51.35	55.79	54.88	51.71	53.98	54.08	1.86
LL	1.05	1.08	0.97	1.04	1.00	1.03	0.93	1.01	0.05
Rel LL	0.62	0.63	0.60	0.63	0.61	0.63	0.57	0.61	0.02
Height	1.69	1.71	1.63	1.65	1.63	1.63	1.63	1.65	0.03
SL @ 5:30	3.19	3.30	3.19	3.30	3.11	3.33	2.92	3.19	0.14
SL @ 5:00	3.45	3.57	3.37	3.60	3.37	3.57	3.13	3.44	0.17
SL rel H @ 5:30	1.89	1.93	1.96	2.00	1.91	2.04	1.79	1.93	0.08
SL rel H @ 5:00	2.04	2.09	2.07	2.18	2.07	2.19	1.92	2.08	0.09
SL rel LL @ 5:30	3.04	3.06	3.29	3.17	3.11	3.23	3.14	3.15	0.09
SL rel LL @ 5:00	3.29	3.31	3.47	3.46	3.37	3.46	3.37	3.39	0.07
SR @ 5:30	1.53	1.48	1.53	1.48	1.57	1.46	1.67	1.53	0.07
SR @ 5:00	1.55	1.50	1.59	1.49	1.59	1.50	1.71	1.56	0.08
VO2 Max	60.5	59.9	56.1	58.7	54.0	54.3	61.8	57.9	3.11
Mile PR	4:55.5	4:52.6	5:03.4	4:35.7	4:58.2	4:42.8	5:01.5	4:52.8	10.14

Participant 2 was another tall steeplechaser similar to participant 1. Her personal best mile was 4:52.6 and this was the third fastest of the group. She was the tallest of the participants with longest leg length, relative leg length, and she tied for the second longest stride length at 5:00 mile pace. Her VO2 max ranked third among the group and her stride rate was in the bottom three of the group. Her data can be found in Table 1.

Participant 3 was the youngest of the group at 19 years of age and came from a soccer background. Her primary event areas were the 5000 and 10000 meter races and her personal best mile time was 5:03.4. This was the slowest mile time of the participant group. She weighed the least of all the group and was one of four participants with the shortest height of 1.63 meters. Her stride length relative to her leg length was the highest of the group and her stride rates at both paces ranked in the top half of the group. Her VO2 max ranked fifth out of the seven participants. Her data can be found in Table 1.

Participant 4 was the fastest and most decorated of all the participants in the study. Her mile personal best of 4:35.7 ranked her among the national collegiate leaders at the end of the outdoor season completed prior to data collection. She possessed a very explosive stride with a very high knee drive during push-off. The motion of her stride resembled a common form seen when athletes are performing bounding exercises. She was tied for being the oldest in the study at 23 years of age and was the third tallest in the study. She also had the third longest leg length and tied for the longest relative leg length. She had the longest recorded stride length of the study at 5:00 pace and the second longest stride length relative to height. Her stride rate was the least of the group at 5:00 pace and her VO2 max placed her as the median of the group. Her data can be found in Table 1.

Participant 5 was a 21 year old with range from the 3000 steeplechase to the 10000 meters. Her personal best mile of 4:52.8 ranked her fourth in the group. She was among the shortest at 1.63 meters in height and ranked fifth in leg length. Her stride lengths at both paces were ranked sixth in length relative to the group. Stride length relative to leg length ranked fifth in the group for both paces. Conversely, her stride rates

at both paces ranked second in the group. Her VO2 max ranked the lowest in the group. Her data can be found in Table 1.

Participant 6 was tied for the oldest at 23 years of age and had the second fastest mile at 4:42.8. She was also ranked among the top 1500 meter/milers in the nation that season. She stood 1.63 meters, a tie for the shortest in the group and was the median leg length. Her relative leg length tied for the highest in the group and her stride length at 5:30 pace was the longest and at 5:00 pace tied for the second longest in the group. Her stride length relative to her height was also the longest at 5:30 pace and tied for second at 5:00 pace. Her stride rate at 5:30 pace was the lowest and tied for second lowest at 5:00 pace. Her VO2 max ranked sixth in the group. Her data can be found in Table 1.

Participant 7 was primarily a 5000 and 10000 meter runner that was 22 years old. She was tied for the shortest in height and also had the shortest leg length, relative leg length, stride length, and stride length relative to height. Her stride rate was the highest in the group for both paces and her VO2 max was the highest recorded for the study. Her personal best mile of 5:01.5 ranked sixth in the group. Her data can be found in Table 1.

Demographic Statistics

The age, height, weight, and leg length of each of the participants was measured on the day of testing. The calculation of leg length relative to height was performed during data analysis. The range of the ages of the participants was 19-23 years with a mean of 21.29 years of age. The range of the heights of the participants was 1.63-1.71 meters with a mean of 1.65 meters. The range of body weight was 51.35-55.88 kilograms with a mean of 54.08 kilograms. The range of leg lengths were .93-1.08 meters with a mean of 1.01

meters. The range of leg length relative to height was .57-.63 with a mean of .61, as seen in Table 1.

Level of Performance and Descriptive Information

The career best personal mile performance and maximal oxygen uptake are considered to be reliable determinants of an athlete's level of performance. The personal best performances of each participant were gathered on the day of testing and the maximal oxygen uptake was measured on the day of testing. The range of mile times was from 4:35.7 to 5:03.4 with a mean of 4:52.8. The range of maximal oxygen uptake was 54.0-61.8 with a mean of 57.9 ml/kg/min as seen in Table 1. Oxygen uptake was measured throughout the protocol in an effort to investigate the significance of oxygen uptake at 5:30 and 5:00 mile pace. No significance was found in this sample population.

Of the seven participants, two would be categorized as being more specialized in the mile run or 1,500 meters with a top end distance of 3,000 meters on the track. Two others would be categorized as steeplechasers outdoors with a range of 1,500 to 5,000 meters. Another two would be categorized as 5,000/ 10,000 meter specialists and the seventh participant would be categorized as an athlete with a range of 1,500 to 10,000 meters.

Stride Lengths at 5:30 and 5:00 mile pace

The stride lengths of each participant were measured during the bouts of running at 5:30 mile pace and 5:00 mile pace. The range of stride lengths at 5:30 pace were 2.92-3.33 meters and the mean was 3.19 meters. The range of stride lengths at 5:00 pace were 3.13-3.57 meters with a mean of 3.44 meters as seen in Table 1.

Stride Length Relative to Leg Length

The stride lengths relative to leg lengths were calculated using the measurement of stride length and dividing it by the measured leg length. This calculation was done for each participant at each of the target paces of 5:30 and 5:00 per mile. The range of stride lengths relative to leg lengths at 5:30 pace were 3.04-3.29 with a mean of 3.15. The range of stride lengths relative to leg lengths at 5:00 pace were 3.29-3.47 with a mean of 3.39 as seen in Table 1.

Stride Length Relative to Height

The stride lengths relative to height were calculated using the measurement of stride length and dividing it by the measured height. This calculation was done for each participant at each of the target paces of 5:30 and 5:00 per mile. The range of stride lengths relative to height at 5:30 pace was 1.79-2.04 with a mean of 1.93. The range of stride lengths relative to height at 5:00 pace was 1.92-2.19 with a mean of 2.08 as seen in Table 1.

Stride Rates at 5:30 and 5:00 mile pace

The stride rates of each participant were measured during the bouts of running at 5:30 mile pace and 5:00 mile pace. The range of stride rates at 5:30 pace were 1.46-1.67 strides per second and the mean was 1.53 strides per second. The range of stride rates at 5:00 pace were 1.49-1.71 strides per second with a mean of 1.56 strides per second as seen in Table 1.

Correlations

The SAS ® (SAS ® Institute, 1994) program was used to analyze all data. A multiple regression and bivariate correlations were used with an alpha level of .05. These first

correlations explore the relationship between peak performance and the variables of height, leg length, and relative leg length. As seen in Table 2, there are no significant correlations between peak mile performance and height, leg length, or leg length relative to height. Relative leg length was the most valuable correlation of the three but it still did not reach statistical significance. Relative leg length accounted for 52.2 % of the variance. The lack of statistical significance may have been due to the relatively low number of participants.

Table 2

<i>Correlations of Physical Measurement Data with Peak Performance (N=7)</i>			
Variable	r	R ²	Sig p<.05
Height	-.097		.836
Leg Length	-.575		.177
Relative Leg Length	-.722	.522	.067

This next group of correlations analyze the relationships between the peak performance (personal best mile time) and maximal oxygen uptake as well as the biomechanical variables of stride length, stride length relative to leg length, stride length relative to height, and stride rate (Table 3). Biomechanical factors only showed statistical significance at the 5:00 pace but were also performed on the data gathered at 5:30 pace. There were two significant correlations and another that was just off significance. The significant relationships with peak performance were stride length at 5:00 minute pace and stride length relative to height at 5:00 pace. The relationship between peak performance and stride rate at 5:00 pace just missed statistical significance as seen in Table 3. Relationships between peak mile performance and maximal oxygen uptake at

both paces, stride length at 5:30 pace, stride length relative to leg length at both paces, stride length relative to height at 5:30 pace, and stride rate at 5:30 pace were found to be statistically insignificant. Stride length at 5:30 mile pace accounted for 48.7% of the variance while stride length at 5:00 pace accounted for 60.4% of the variance. Stride length relative to height at 5:30 and 5:00 pace accounted for 47.8% and 65.4% of the variance respectively. While stride rate at 5:30 pace accounted for 46.9% and stride rate at 5:00 pace accounted for 56.5% of the variance.

Table 3

<i>Correlations of Physiological and Biomechanical Data with Peak Performance (N=7)</i>			
Variable	r	R ²	Sig p<.05
Maximal Oxygen Uptake @ 5:30 pace	.120	.014	.798
Maximal Oxygen Uptake @ 5:00 pace	.120	.014	.798
Stride Length @ 5:30 pace	-.698	.487	.081
Stride Length @ 5:00 pace	-.777*	.604	.040
SL relative to LL @ 5:30 pace	-.044		.925
SL relative to LL @ 5:00 pace	-.349		.443
SL relative to H @ 5:30 pace	-.692	.478	.085
SL relative to H @ 5:00 pace	-.808*	.654	.028
Stride rate @ 5:30 pace	.685	.469	.090
Stride rate @ 5:00 pace	.752	.565	.051

Note: SL = Stride Length, LL = Leg Length, H = Height

The hypothesis was analyzed using a multiple regression. Table 4 contains means, standard deviations, and Pearson correlations. Four predictor variables were assessed

stride length relative to leg length, stride rate, max VO2 and mile PR. Significance was found between variables leg length and stride rate ($r=-.89$), relative leg length and stride rate ($r=-.98$), stride length relative to height ($r=-.90$), stride length and mile PR ($r=-.78$), and stride length relative to height and mile PR ($r=-.81$) at 5:00 pace. The only statistically significant relationships found at 5:30 mile pace were stride rate and stride length relative to leg length ($r=-.94$), leg length and stride rate ($r=-.81$), and stride length relative to height and stride rate ($r=-.90$) as seen in Table 5.

Table 4

Means, Standard Deviations, and Correlations at 5:00 Mile Pace (N = 7)

Variable	<u>M</u>	<u>SD</u>	slrelll	Intercorrelations		
				sr	vo2max	milepr
1. Height	1.65	.03	-.73	-.45	.53	-.10
2. LL	1.01	.05	-.32	-.89*	-.01	-.57
3. rel LL	0.61	.02	.02	-.98*	-.31	-.72
4. SL	3.44	.17	.15	-.99*	-.28	-.78*
5. SL rel H	2.08	.09	.50	-.90*	-.57	-.81*
6. SL rel LL	3.39	.07	1.00	-.13	-.55	-.35
7. SR	1.56	.08	-.13	1.00	.29	.75
8. vo2max	57.9	3.11	-.55	.29	1.00	.12
9. milepr	4:52.8	10.14	-.35	.75	.12	1.00

* $p < .05$

Table 5

Means, Standard Deviations, and Correlations at 5:30 Mile Pace (N = 7)

Variable	<u>M</u>	<u>SD</u>	slrelll	Intercorrelations		
				sr	vo2max	milepr
1. Height	1.65	.03	-.73	-.36	.53	-.10
2. LL	1.01	.05	-.47	-.81*	-.01	-.57
3. rel LL	0.61	.02	-.16	-.94*	-.31	-.72
4. SL	3.19	.14	.12	-.99*	-.35	-.70
5. SL rel H	1.93	.08	.48	-.90*	-.64	-.69
6. SL rel LL	3.15	.09	1.00	-.13	-.52	-.04
7. SR	1.53	.07	-.13	1.00	.37	.68
8. vo2max	57.9	3.11	-.52	.37	1.00	.12
9. milepr	4:52.8	10.14	-.04	.68	.12	1.00

*p < .05

Chapter 5

CONCLUSION, DISCUSSION, AND RECOMMENDATIONS

Conclusion

In conclusion, the participants in this study seem to mirror the wealth of knowledge regarding the importance of stride length and stride length relative to height as key factors in a peak running performance in the mile run. The findings regarding the importance of maximal oxygen uptake may not have been as strong as the findings regarding stride data, however, maximal oxygen uptake is clearly an important factor in the conditioning necessary to run 5:00 mile pace. Stride rate relationships were valuable and with a larger sample, may have grown toward an increased level of significance. The sample population must be taken into account when viewing this data since the seven participants form a relatively homogenous group in terms of the variables measured. It seems that a focus on the increasing of stride length with the increased force of push off and a more forceful leg drive can effectively be used to help these female athletes improve over the course of their careers. These changes may come about through increased focus and attention to the push off and leg drive as well as strength training and flexibility routines that can increase the mobility and strength in the hip region. Stride length is certainly one important factor in the peak performance of these elite female collegiate distance runners and the proposed hypothesis was supported by the data and results of this study.

Discussion

Although this research was based on a relatively small sample, all seven of these women were considered elite collegiate distance runners. These seven women provided excellent

data that can be used to provide valuable insights into the interactions between physiology, biomechanics, and peak distance running performance in female collegiate distance runners. For example, the physiological parameter of maximal oxygen uptake has been deemed a logical determinant of performance (Billat, Lepretre, Heugas, Laurence, Salim, & Koralsztein, 2003) as well as a tool to gauge the fitness of individuals from different athletic backgrounds (Nevill, Brown, Godfrey, Johnson, Romer, Stewart, & Winter, 2003). However, the data collected in this research suggest that maximal oxygen uptake has very little correlation with the peak performance parameter of the one mile run. It may be the case that the mile run is too short a distance for maximal oxygen uptake to be considered valuable since all of our subjects completed the mile run faster than five minutes and four seconds. If manipulated in a similar population with the peak performance being a 10,000 meter personal best, maximal oxygen uptake may have been found to be more valuable. Unfortunately, in this sample, very few of the participants had ever participated in a 10,000 meter race.

In this study, the women showed some reasonably strong yet not statistically significant correlations between stride rate and performance at both of the testing speeds. It is stated in some research circles that stride rate is predetermined by heredity (Scholich, 1978) while others state that stride rate actually decreases as fatigue increases (Williams, Snow, & Agruss, 1991). This study could not address the genetic predisposition of stride rate and other related factors. However, results in this study showed a slight mean increase in stride rate from 5:30 mile pace (4.87 meters/second) to 5:00 mile pace (5.36 meters/second). These results appear to fall in line with the current stream of research supporting the primary source of increased speed during distance running is stride length

with stride rate staying relatively steady and possibly increasing slightly as a by-product of the increase in velocity. The correlations reported in this study also show an important relationship between stride rate and performance. Stride rate at 5:00 mile pace was found to have a very positive correlation with the fastest mile time ($r=.752$) with a significance of $p=.051$. It can be surmised that stride rate is a valuable component of peak performance, just not as important as stride length.

The data from this study supported a strong relationship between stride length and peak performance. Significant relationships were reported for stride length at 5:00 mile pace and performance as well as the ratio of stride length to height at 5:00 mile pace and peak performance. It has been stated that height and stride length are not correlated with each other (Cavanagh & Kram, 1989) and that may appear to be supported by some of the data gathered in this study. All of the participants in this study were within 8 centimeters of each other in height. However, there was a 15 centimeter range in leg length, 41 centimeter range in stride length at 5:30 pace, and a 44 centimeter range in stride length at 5:00 mile pace. These data support research stating the importance of a more powerful leg drive as a means to increase stride length at increasing velocities (Hogberg, 1952b). When observing Participant 4 on film it was noted that she had a very powerful knee drive which contributed to her relatively high stride length measurements along with the fastest mile recorded in the study. With an increase in leg drive at the push-off phase of gait, an increase in the float time and distance leads to an increase in stride length (Scholich, 1978) regardless of height or leg length. But the statistical analysis in this study showed the most statistically significant finding of the study to be the correlation between stride length and height relative to peak performance. In this

study, this relationship is clearly a serious factor in the peak performance of these participants. However an increase in stride length relative to leg length at 5:00 pace as well as an increase in stride length relative to height at 5:00 pace was also found when analyzing the data of the seven participants. These results could also be supported by the theories regarding increased leg drive and push-off leading to increased float and stride length. Especially since the participants in this study are relatively homogenous in terms of height, weight, and leg length.

The importance of the significant relationship between stride length and performance is found throughout the literature. Increased stride lengths were reported to be one of the serious performance difference makers in the 1984 US Olympic Trials marathon for women (Buckalew, Barlow, Fischer, & Richards, 1985) as well as the common belief that an increase in stride length causes an increase in velocity (Knuttgen, 1961). In this study, stride lengths increased with the increasing speed supporting previous literature. This trend is reported for both sprinters and distance runners alike. Sprinters accelerate using an increase in stride length as the means to increase speed up until the point of sprinting. At that point, stride rate is deemed the most valuable component of running velocity (Weyand, Sternlight, Bellizzi, & Wright, 2000). Since our sample was clearly not made up of sprinters, the results obtained were expected.

The use of an increase in stride length as a means to increase shock attenuation is also supports the use of stride length as a valuable component of peak performance. Mercer et al. (2003) found that an increase in stride length due to fatigue was accompanied by an increase in shock attenuation. Coaches can take this useful information and apply it to their training schemes and philosophy. Simple factors like

changing running shoes before they experience breakdown and careful attention to avoid overtraining can also be helpful in increase of shock attenuation and thus increase the possibilities of the athlete remaining healthy and injury free. This increase in stride length with fatigue can play a major role in the maintenance of training at a sub-maximal pace on daily training runs.

The increase in stride length as the primary means of increasing running velocity up to 5.5 meters per second was reported in a study looking at forty-two elite female distance runners (Gregor, Rozenek, Brown, & Garhammer, 1979). The data collected in this study agree with these findings as the two significant findings focus on stride length relationships at 5:00 mile pace, just below the 5.5 meters per second used by Gregor et al. The importance of stride length relationships are even seen at the slower test speed of 5:30 pace per mile. The strong relationship between stride length and height at 5:30 pace relative to peak performance mirrors the relationship and correlation between stride length and peak performance at 5:30 pace. These relationships also show the importance of stride length relationships and peak performance at sub-maximal speed.

Several studies of female runners investigated and support the data collected during this study. The correlation of stride length to height in this study was found to be $r=.439$ which is nearly identical to the correlation of $r=.43$ found by Williams, Cavanagh, and Ziff (1987). Another study (Powers, Hopkins, and Ragsdale, 1982) concluded that female runners require less energy to run at their naturally chosen stride length at a sub-maximal level. This is relevant to this study in that running at sub-maximal levels is a regular component of training for this participant group and running economy is a valuable tool in the determination of performance.

Stride alterations may also take place due to possible changes in running form when inexperienced treadmill runners participate in a protocol on a treadmill. Creagh, Reilly, and Lees (1998) reported that female distance runners altered their stride length significantly in response to the difficulty of the running terrain. In this case, the difficult terrain was the motorized treadmill. There is a chance that the running mechanics of the participants was altered due to the novelty of running on a treadmill.

Interest in running performance of female collegiate distance runners is at an all time high point. Contracts are more available and more lucrative for many young women after college than they have ever been in the past for American collegians. The competitive fields are getting faster and faster with the difference between victory and defeat now being defined in terms of tenths of seconds instead of seconds. World class marathon races are now settled by a sprint kick to the finish and finish line results now must be computerized in order to separate competitors as they cross the finish line. American collegiate veterans like Deena Kastor are now winning Olympic medals in the distance races partially due to the financial freedoms afforded her by her lucrative endorsement contracts. We are at a point in collegiate female distance running that it is time to take the next step and start to focus more on these athletes as subjects of the next wave of biomechanical and physiological research in order to give the future generations of female distance runners more chances to get closer to their male counterparts both on and off the track.

Recommendations

1. Future stride research should include more collegiate female athletes that either are already elite or are preparing to be elite in their events.

2. This study should be duplicated with a larger sample size of women as well as a matching sample of elite male collegiate distance runners to test any gender differences among this age group and skill level.
3. Future research should focus on the methods used to increase strength of leg drive and push off during the gait cycles of distance runners.
4. Future research should also include other biomechanical considerations like knee angle, hip angle, degree of pronation, and heel strike.
5. Future research should also replicate this study with the 40 male and female participants at the Foot Locker High School National Cross Country Championships.
6. The PEAK system should be used with more frequency for the study of the mechanics of distance running.

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APPENDIX A
Informed Consent

Maximal Treadmill Testing
INFORMED CONSENT

Title

The Relative Contributions of Stride Length, Stride Rate, and Maximal Oxygen Uptake to a Peak Performance by Elite Female Collegiate Distance Runners

Investigators

Michael Garrison, University of Arkansas PhD Candidate
Dr. Ro DiBrezzo, University of Arkansas Professor

Explanation of the Test Protocol

You will perform a maximal graded exercise test maximal. This will be performed in order to assess the functional capacity of your heart, lungs, and blood vessels. This specific test will be performed on a motor driven treadmill. The test will begin at a level which you can easily achieve and is increased until maximal oxygen uptake is reached. This test is designed to determine the your maximal oxygen uptake while running at a pace nearly identical to a racing effort. You may stop the test at any time when you feel that you have reached a level in which you can no longer continue. The testing will take approximately 30-40 minutes.

Risks and Discomforts

There exists the possibility of certain changes occurring during the fitness assessments. They include, but are not limited to, muscle or joint injury, abnormal blood pressure, fainting, disorders of the heart beat, and in rare instances heart attack, stroke, or even death. Every effort will be made to minimize these risks through preliminary evaluations and observations during the tests. Trained personnel will be available during testing at all times in the event an unforeseen instance may arise.

Responsibilities of the Participant

Any information you possess about your health status or previous experiences of unusual feelings with physical exertion may affect the safety and value of your exercise test. Your prompt reporting of such feelings during the test is of great importance. You are responsible to fully disclose such information when requested to the testing staff.

Benefits

The results obtained will assist in the research concerning biomechanical and physiological limitations during a peak running performance. This study will add to the knowledge base of coaches, physiologists, and biomechanists.

Inquiries

You may ask any question at any time during any of the testing procedures. If you have inquiries please ask the laboratory personnel for further explanation.

Confidentiality

Only the researcher, research assistants, and the participant will have knowledge of the results of each participants exercise test. These will be the only people present in the lab during testing and only the researcher will have access to all data during data input into biomechanics software and statistical software.

Freedom of Consent

Permission for you to engage in the testing and exercise protocol is voluntary. You are free to deny or withdraw from testing at any time if you so desire. Refusal to participate will carry no penalty. I have read this form and understand the test procedures that I will perform and I consent to participate.

I understand that participation in all activities in the HPER Building, or in any other program sponsored by the HKRD Department, regardless of location, is voluntary on behalf of all participants. I acknowledge and agree that the University of Arkansas does not provide insurance for any of its activities and shall not be liable for any injuries that occur at any of these locations or in any of its programs.

Participant_____ **Date**_____

Witness_____ **Date**_____