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THREE-DIMENSIONAL QUANTITATIVE ANALYSIS OF THE TRAJECTORY OF THE FOOT WHILE RUNNING

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ABSTRACT OF THESIS

THREE-DIMENSIONAL QUANTITATIVE ANALYSIS OF THE TRAJECTORY OF THE FOOT WHILE RUNNING

Exercising the leg in a manner similar to running is theorized to have the potential effect of increasing performance and reducing occurrence of injuries in running athletes. Development of an exercise device that can help facilitate this method of specificity training could be beneficial to the sports community and should be investigated. Understanding the trajectory of the foot during the running gait is primary to further pursue this concept.

26 running athletes of varying characteristics participated in this study. Each subject’s sex, age, weight, height, leg length, activity level and participation amount in their respective sport was recorded. Retro-reflective cameras captured the three-dimensional trajectory of each subject’s right leg while running at speeds of 2, 3.8, 4.52 and 5.36 m/s for 10-15 seconds on a treadmill, respectively. The range of foot movement in each cardinal plane was determined for each speed.

An ANCOVA revealed that leg length was the most determinate factor in trajectory range differences among subjects. Subjects were subsequently divided into quartiles based on leg length where further analysis revealed that foot displacement increased vertically and horizontally in the sagittal plane with increases in speed while trajectory in the third plane remained constant and substantially less in magnitude.

KEYWORDS: Trajectory, Running, Kinematics, Specificity, Three-Dimensional

Thomas J. Cunningham

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December 14, 2007
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Thomas J. Cunningham

The Graduate School
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2007
THREE-DIMENSIONAL QUANTITATIVE ANALYSIS OF THE TRAJECTORY OF THE FOOT WHILE RUNNING

THESIS

A Thesis Submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Education at the University of Kentucky

By

Thomas J. Cunningham

Lexington, Kentucky

Director: Dr. Timothy L. Uhl, Associate Professor of Rehabilitation Sciences

2007

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Chapter I

Introduction

Running, especially sprinting, is a very common component of nearly every competitive and recreational sport. The ability to sprint is a skill that is enhanced by training mental[1], cardiovascular[2], neuromuscular[3], and musculoskeletal[4] systems. Competitive and recreational athletes with better ability to sprint or those that can sprint more often in their respective sport are commonly rewarded in accolades and in professional sports financially. For sports where a major component of performance that is considered acceptable is based on the ability to run and sprint effectively this skill is important to train.

A method of training that has become accepted amongst coaches and personal trainers is to functionally train individuals in a manner that is specific to their respective sport as opposed to training methods that isolate specific muscles involved in that sport.[5] This concept of training in a similar manner to how you will compete is intuitive but implementing exercises that can apply resistance to these functional movements has proven to be difficult in many sports. Creative exercises have been developed and implemented into exercise regimens that mimic certain functional tasks demanded by the desired activity or sport such as propelling and resisting a runner to supra-maximal and sub-maximal speeds during training for track,[6] or ballistically training athletes for improvement in their vertical jumping height.[7] Fundamentally similar training methods which focus on specificity training have shown positive but limited results of improved performance in the execution of these functional tasks and the
potential to reduce injuries particular to movements commonly practiced in a respective sport.

Hamstring injuries have been identified as some of the most common injuries to occur in sports requiring a significant amount of running and sprinting activity such as soccer, Australian rules football, American football\(^1\), and track.\(^{[8-10]}\) A study of English professional football (soccer) has shown that hamstring injuries account for 12-15% of all injuries sustained.\(^{[10]}\) These findings are consistent with a recently concluded 14 year epidemiological study of NCAA men’s soccer that reported muscle strains to the upper thigh constituted 8.6% of all injuries sustained during games and 16.6% of injuries sustained during practice.\(^{[11]}\) Injuries also have an economic impact. The English premier football league reported a gross revenue of close to $3.8 billion in the 1999-2000 season with injuries alone costing as much as $144.7 million.\(^{[12, 13]}\) Hamstring injuries are common occurrences in athletes and currently there is not a clear understanding of what factors predict this type of injury. Muscle strength, flexibility, fatigue, and neuromuscular control are some of the most common factors commonly thought to be associated with hamstring injuries.\(^{[14-16]}\) Additionally, these factors are critical components in enhancing sprint performance through sports specific exercises.\(^{[17]}\)

Measures need to be taken in order to further understand hamstring injuries with the goal of reducing the amount of hamstring injuries occurring each year. Researchers are constantly evaluating the scientific literature for promising exercise interventions that can be utilized both in the prevention and rehabilitation of injuries and performance enhancement. Training methods to improve running performance while reducing the

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\(^1\) The sport is commonly termed Soccer in North America and Football in other countries unless specified American Football which is a different sport commonly played in North America.
occurrence of the hamstring running injury mechanism might reduce the cost and incidence of injuries.

It is our hypothesis that to enhance an athlete’s performance in a specific activity and reduce the risk of injury occurrence during that activity, it is beneficial to train the athlete in a manner that mimics the activity as closely as possible. More specifically, if the activity is running, it would be beneficial to create a training environment that simulates the lower limb motions involved during running. Consequently, by training the lower limbs appropriately, it is possible that running performance might be enhanced while the chance of incurring a hamstring strain might be reduced. Unfortunately, equipment to aid in this area of training has not yet been developed.

**Problem Statement**

If an exercise device were to be designed to accurately simulate the running system, the fundamental component of this system should be founded upon an in-depth knowledge of the trajectory of the limb in question. In order to reach this conclusion, one should consider the fundamental method for propelling oneself forward during running. This propulsion is accomplished by kinetic forces originating from the reaction force exerted from the ground to the contact point of the foot and finally translating throughout the leg to the body’s center of mass.[18-20] Following Newton’s third law of motion, all propulsive forces in running act along the opposite vector of the trajectory of the point in contact with the foot.[18, 20] Therefore, during specificity training, one could conclude that forces need to be applied along the trajectory of the foot in order to properly train the leg. To accomplish this goal, the trajectory of the foot during running needs to be documented and well understood.
Purpose Statement

The purpose of this study is to quantitatively describe the trajectory of the foot while running at various speeds. Two questions are to be answered with this study. The questions are as follows:

1. What effect does speed have on the end point trajectory of the foot during running?
2. What effect do the factors of height, age, leg length, sex, activity level and participation amount have on predicting the end point trajectory of the foot during running.

Significance of Study

Experiments involving the application of resistances to the foot while accurately simulating running cannot be undertaken without first mapping the trajectory of the foot with respect to an array of possible factors. Additionally, knowing the quantitative characteristics of the foot trajectory while running will add to the existing body of knowledge of the running gait and hopefully provide a step in building a tool to improve many aspects of running.

Delimitations

The delimitations of this study are as follows:

1. 26 runners above the age of 18.
2. A heterogeneous sample varying independent factors such as height, weight, leg length, age, sex, activity level and participation amount.
3. The use of a treadmill as a running platform opposed to overground running.
4. The use of an ordinal scale in determining activity level and participation amount.

5. The 4 selected data collection speeds.

6. The order in which the speeds are run.

7. Warm up protocol.

8. Data collection dates.

9. Data calculations performed to describe data.

10. Processing parameters of data such as 200 Hz collection frequency and filtering bandwidth.

11. Conditioning subjects to the treadmill on the same day rather than on a previous day.

12. The use of only one side of the body to describe the bilateral motion of running.

The above delimiting factors were chosen by the author to represent the believed main contributing delimitations to this study, but as with any clinical study, more delimitating factors undoubtedly exist; however, additional delimitations were considered relatively negligible.

Limitations

There are several limitations that will have an effect on the questions being asked. They are as follows:

1. The sample size is relatively small (N=26) necessitating caution in extrapolation of the data to the large running population.

2. Daily activities of the subjects other than the running program will not be controlled.
3. The ability of subjects to familiarize themselves to the treadmill. This will inherently differ between every subject and will not be addressed other than during warm up and same day treadmill acclimation.

4. The effect of the treadmill on running kinematics and its inference to describe overground running. This should be minimized for the first three speed categories. Kinematics have been shown not to differ at these speeds between overground and treadmill running; however, for speeds greater than 4.8 m/s, the factors such as stride length and frequency have been observed to significantly change, however, these speeds are still lower than maximal speeds observed in previous studies.[21] [22]

5. Instrumentation error with the 3-D camera system and speed of the treadmill. Calibration techniques should minimize this error to be negligible.

**Hypotheses**

Quantitative data will be used to test these following hypotheses.

1. Concerning subject factors:
   a. Activity level and running speed will contribute significantly to the differences in trajectory path.
   b. Large differences in height and leg length will contribute to trajectory path differences slightly.
   c. All other subject factors will contribute insignificantly.

2. The horizontal foot displacement range will increase with speed.

3. The vertical foot displacement range will increase with speed.

4. The depth foot displacement range will decrease with speed.
Definition of Terms

To avoid confusion some terms and phrases applicable to this research should be defined. It is recognized that there is currently debate when defining the differences among walking, running and sprinting. For the purpose of this study, the definitions of these terms are based on the desired outcome of the individual while not ignoring mandatory mechanical characteristics seen at each respective speed category.

Activity Level: A gauge of the skill and running application of subjects with ordinal categories consisting of varying degrees of non-competitive and competitive levels.

Depth Dimension: Vectors normal to the plane created between the Horizontal and Vertical Dimension. Pictured as “Depth” in Figure 3.2.

Foot Displacement Range (FDR): The difference between the maximum and minimum value seen during a gait cycle for a given dimension.

Horizontal Dimension: Vectors parallel to the lengthwise edge of the treadmill. Pictured as “Horizontal” in Figure 3.2.

Participation Amount: Self reported amount of days a subject ran above 50% of their self-assessed maximum intensity during a given week.

Running: Has a period of double float (no foot is on the ground) with foot contact being near the rear or mid-foot. Energy is conserved during this movement.[23]

Sprinting: Like running, also has a period of double float but the goal is to move the limbs as fast as possible with no regard to aerobic cost. Foot strike is at the forefront of the foot.[23]

Stance Phase: Phase of gait when the foot is in contact with the ground

Step: Half the stride encompassed by two consecutive foot-strikes (i.e., right to left).[24]
**Stride:** One gait cycle which begins when one foot strikes the ground and ends when the same foot strikes the ground again.(ipsilateral to ipsilateral foot strike)

**Swing Phase:** Phase of gait when the foot is not in contact with the ground.

**Vertical Dimension:** Vectors parallel to the normal vector of the surface of the treadmill.

Pictured as “Vertical” in Figure 3.2.

**Walking:** Has two periods of double support in each gait cycle, meaning that both feet are in contact with the ground simultaneously.[25]
Chapter II: Review of Literature

The aim of this chapter is to develop an evidence based summary concerning previous research on running with the goal of constructing an argument for further investigations involving the running gait and its relation to functional training. The structure for this review has two elements. The first is to describe information available on the running gait and possible parameters not investigated thoroughly. The second is to identify a mechanism of injury during running that could be addressed with information provided from a study regarding the first topic. After review, topics of emphasis are the trajectory of the foot during running and the hamstring injury mechanism. These are discussed below.

Trajectory

Running gait kinematics has been a focus of extensive research for forty years. Many studies have progressed to document joint kinematics and kinetics for three dimensions (3-D) as called for by previous two dimensional (2-D) studies and reviews. These two parameters, joint kinematics and kinetics, are well understood in two dimensions, sagittal and frontal with information on the third, rotational, somewhat lacking.[23] Unfortunately, less information has been reported for trajectories in 3-D either qualitatively or quantitatively. In a discussion concerning predicting subtle movements found in gait, Mah[26] discussed his opinion that most movements in gait occur in the sagittal plane. This statement can be attested to by biomechanists just from observing data from their respective studies; however, there is no published data supporting this statement. Analyzing the trajectory of the foot in three dimensions will provide quantitative data which will possibly give credence to statements similar to that above.
Despite the vast amount of literature describing the running gait, trajectories of anatomical landmarks such as the ankle are lacking. A method for quantitatively describing the trajectory of the lower limb while running has not yet been published. Early kinematic works by Cavanah[20] and Hoshikawa [27] have described the position of the ankle at various speeds of the running spectrum using path diagrams which trace the path of a landmark throughout the gait cycle in the sagittal plane. These descriptions have been mostly qualitative giving just a tracing of the foot path. Cavanagh did publish a subset of sagittal plane coordinates of the ankle for a subject running at 3.8 m/s as well as values describing the range of the foot both horizontally and vertically for several submaximal speeds. Cavanagh’s data was collected on a treadmill for two continuous gait cycles. Cavanagh did not elaborate on any methods for making relative comparisons for his coordinate data along the lines of normalization which is apparent in his overlapping path diagrams. He did however report the distance the ankle was in front of the hip at foot contact. The reporting of data relative to the hip might infer that when normalizing and comparing coordinate data, the data should be offset to the hip rather than an arbitrary foot contact point.[20]

Despite the lack of trajectory publications for running, extensive reports describing walking trajectory are available. A study by Ivanenko, (et. al, 2002)[28] describes in great detail the quantitative measures that are to be discussed with this project. Ivanenko was evaluating the effect body weight had on the foot trajectory at speeds ranging from an extremely slow walk of 0.4 m/s to 1.8 m/s which is near the transition speed of walking to running for many individuals.[20] Ivanenko had several categories of body weight (including full body weight) with data analysis procedures
being the same for all categories. The parameters reported by Ivanenko that are of possible concern for this study are stride length, vertical displacement of the foot, surface area of the closed endpoint path, and arc length of the surface path. Path diagrams presented by Ivanenko are similar to those reported by Cavanagh. Obvious differences are that the subject’s are walking opposed to running. Ivanenko’s path diagrams over the full spectrum of walking speeds show a distinguishable progression of elongation of the foot path in both the horizontal and vertical directions as speed increases. Ivanenko, unfortunately, also did not report foot displacement in the third dimension possibly because, as mentioned earlier, it is thought that the overall movement of gait mostly occurs in the sagittal plane. His procedures can be used, with slight mathematical modification, to similarly analyze the third dimension and possibly make a rational argument to significantly bias training to sagittal plane movements when describing the end point trajectory of the foot during gait. One additional insight Ivanenko described was the use of the treadmill and comparing separate gait trials. Ivanenko described a process for taking all lower leg motions relative to the hip and then offsetting all hip movement to a fixed lab coordinate point. A marker set was also described to capture trajectory of the lower limb when other kinematic and kinetic variables are not needed.

**Parameters**

Stride length and stride frequency have been thoroughly documented. Stride length is a larger contributing factor to speed than stride frequency.\[29\] As speed increases, stride length also increases while stride frequency stays relatively the same.\[25, 29, 30\] However, the limit to stride length’s influence on speed is emphasized while reaching maximum speeds. Attempting to reach top speeds shows increases in stride frequency
rather than increases in stride length which holds relatively constant.\[19, 25, 29\] This information is useful in the formation of a hypothesis of how the characteristics of the foot path will change as speed increases. This information suggests that the horizontal distance traveled by the foot will increase as speed increases thus elongating a trace of the foot path in the sagittal plane until a higher speed is reached, where the footpath should remain fairly constant and the foot should then traverse the path more rapidly.

With the variable of stride length seemingly contributing to gait characteristics more than others, factors such as height, trochanteric leg length, age and weight have been investigated for their relationship with stride length.\[20, 25, 31\] Height and leg length were found to positively correlate with stride length but were surprisingly weak in magnitude.\[20, 25\] Age and weight have seen conflicting results but are considered to be minimal contributing factors to stride length.\[20\] These findings have been similar for both genders.\[25\] These factors have been identified as generally contributing to the characteristics of the gait cycle, although some evidence suggests otherwise when just looking at stride length.\[29\] Other factors such as muscle fiber type, training background and other physiological factors have been suggested to contribute to stride length with training background being the most significant.\[31\]

After review, it seems more probable that stride length might be a dependant function of speed due to the required horizontal distance needed to maintain speed \[25\] rather than the reverse. If speed dictates stride length, the running path characteristics should mostly be predicted by speed. This would then suggest that other typical predictive factors such as height, leg length, age, and weight should cautiously be examined when being used in the prediction of the trajectory of the foot.\[20\]
Nevertheless, these factors as well as training background should be recorded with a study involving the three dimensional analysis of trajectory in order to possibly correlate characteristics of the paths to these commonly recorded measures. Physiological factors and muscle type are not commonly recorded and difficult in the application of determining a desired running path so therefore should be omitted for initial descriptive studies but should possibly be further examined at a later date.

**Hamstring Injuries**

From a medical perspective overuse injuries and traumatic muscle strains are common complaints of running and sprinting athletes. Several studies which have followed sports clubs commonly report muscle strains, in particular strains of the hip flexor, adductors, and hamstrings as being the most problematic accounting for up to 14% of total injuries sustain and most game time lost. [9, 10, 12, 32] Despite the high instances of hamstring injuries, the exact cause and timing is still unknown. There are two prevailing theories that exist as to the phase of gait in which hamstring strains occur.

1. The first theory states that the late swing[4] and early stance[18] phases of sprinting are the most predominant phases of gait where hamstring injuries occur.[33] During late swing, the knee is extending and the hip is flexed. The hamstring muscles are eccentrically contracting to decelerate hip and knee extension in preparation for heel strike.[8] Lengthening the hamstring muscles during activation could induce an eccentric contraction injury.[34] Directly following late swing, the hamstring muscles continue their activation and concentrically contract which, conversely, could induce a concentric muscle strain.[18, 35]
A case study presented recently by Heiderscheit et al. (2005)[36] documented a hamstring injury while collecting kinematic data of an athlete running on a treadmill. The subject was running relatively fast at 5.36 m/s and it was determined that the subject’s biceps femoris was strained just prior foot contact in late portion of the swing phase. The biceps femoris has been reported as being significantly injured more often than the other hamstring muscles at an incidence upwards to 80%.[14] This case study supports the theory that hamstring injuries occur at this time in the gait cycle.

2. The second theory hypothesizes that injury is most likely to occur later in the stance phase at toe-off where the length of the hamstring muscles aren’t at their longest but where the largest peak torque levels are observed.[33, 37, 38] Like early stance, if injured during this phase, the injury would be concentric in nature due to the concentrically contracting hamstrings which are assisting in hip extension.[8] Despite the evidence provided by Heiderscheit et al. (2005), the dismissal of this second theory would be premature. The first theory discussed may describe the majority of hamstring strains but current evidence cannot disprove the possibility of this second theory. Due to this reasonable second theory and a lack of evidence to disprove, this aspect of the running gait should still be considered an important aspect of preventing and rehabilitating hamstring injuries and properly training an individual.

Late swing phase as well as late stance phase occur at significantly different phases in the gait cycle. Being unable to rule out either possible phase for hamstring injuries, it is mandatory to at least study these two distinct aspects of the gait cycle. With the gait cycle being periodic in nature all aspects of the gait cycle should still be investigated.
Contributing Factors

One single factor has not been identified as predominant when evaluating the injury mechanism of strained hamstrings.[13] The current literature suggests that there are several contributing factors which can cause hamstring injuries.[39, 40] The primary factors are further discussed. Each factor’s contribution to a possible exercise machine application is further commented on.

Quadriiceps and Hamstring Strengths

Low hamstring strength is theorized as being a cause of hamstring injury.[16] A high ratio of quadriceps strength to hamstring strength has further been suggested to increase the probability of a hamstring injury.[16, 41] This, however should not necessarily suggest that a weakness in hamstring strength is needed to cause injury, but rather just a disproportional quadriceps to hamstring strength ratio.[39] It has been suggested that eccentric muscle strength may be a more significant factor than concentric muscle strength as a determinant of injury due to the functional eccentric role of the hamstrings during running gait.[42] Results from exclusively testing eccentrically do not, however, confirm this theory.[43] The same can be said about measuring muscle strength concentrically.[44] With all these conflicting results it is very difficult to draw any strong conclusions on the proper way to strengthen the leg muscles.

When considering quadriceps and hamstring strengths as causes for hamstring injuries, it might be less appropriate and very limited to solely use concentric and eccentric strength evidence as predictors of hamstring injuries but more appropriate to look at previous strengthening program results when determining what factor muscle strength has on hamstring injuries. It is has been found that increasing eccentric strength
can improve the ability of a muscle to withstand forces and subsequently not fail. [45] Current training regimens may involve increasing lower limb strength in general and might induce excessive quadriceps strength which might lead to injury. [13, 39]

A program involving training of the quadriceps and hamstring muscles, simultaneously, and over the entire range of applicable forces and speeds, might serve as the best method for training the hamstrings correctly to reduce injury rates. [5, 46] There is currently not a machine available on the market that is capable of fulfilling this recommendation.

Muscle Fatigue and Neuromuscular Control

Many neuromuscular events take place during the running gait in order to control hip and knee motion in late swing and provide hip extensor torque in early stance. [39] Since running is a relatively fast motion, these events occur over a very short period. If control and coordination are inadequate, muscle strain injury might result. [41, 47] It has been suggested that a method for adequately training the hamstrings must include improving neuromuscular control of the leg during swing phase. [39] If an error is made in the control of the swinging leg at times when high hamstring forces exist, a strain is possible. [39]

During the swing phase, when hamstring muscles are eccentrically contracting and decelerating the lower leg, high forces are generated and if fatigue occurs an injury may result. [40] Improper synchronization of the dual innervation pattern seen between the short head of the biceps femoris and the remainder of the hamstring muscles might introduce an injury mechanism. A mistiming on contraction of the biceps femoris due to fatigue might reduce the ability of the hamstring muscles to generate sufficient forces and
lead to a hamstring injury[13, 41] Improving neuromuscular control of the leg during the swing phase is recommended for reducing the likelihood of incurring a hamstring injury.[39] Actively assisting limbs along a predetermined trajectory has been found to increase neuromuscular control of the assisted limb when the limb is no longer in a controlled environment for stroke patients.[48] Authors in this specific field of study speculate that this fundamental trajectory gait training might translate to the workplace and sport by enabling people to perform a learned specific task repeatedly upon command without practice.

Individuals who exhibit poor neuromuscular control during injury prone movements have been trained to correct these neuromuscular deficiencies and consequently reduced their chance of injury.[49] Over the past decade the ACL mechanism of injury for female athletes has been exhaustively studied. One focus of ACL prevention research was identification and correction of biomechanical and neuromuscular deficits amongst athletes. In several cases, functional training was introduced to correct these neuromuscular deficits and injury rates diminished.[50, 51] These findings have not yet been applied to the hamstring muscle mechanisms of injury. This might be in part due to the lack of a proper machine to facilitate this functional training. Taking the above information into consideration, actively assisting the foot while mimicking the swing phase of running, might help improve the neuromuscular control of the lower limb.
Flexibility

Muscle flexibility is said to reflect the muscle’s ability to lengthen and absorb forces.[13] Contrary to commonly held beliefs that flexibility is the key to preventing injury[16] most evidence is contradictory and questions manifest whether muscle flexibility is a potential risk factor for injury[15], a consequence of other factors which lead to injuries[8] or even a predictive factor at all[47]. The latter takes a controversial stance but seems to be the most concerning and have the most clinical relevance. Recent work by Witvrouv et al (2003)[52] found that among 146 soccer players investigated in a prospective cohort injury study, 31 incurred a hamstring muscle strain. Of those, hamstring tightness was the only statistically significant commonality amongst the injured population. In direct contrast, Bennel et al (1999)[47] found that there was no correlation between results from the toe touch test, a commonly used and reliable hamstring flexibility test[53], and injury rate occurrences for an Australian Football club consisting of 67 players. It would be premature to extrapolate these results to an entire population and discount stretching as a tool to prevent hamstring injuries but more in order to further investigate the effectiveness of actively stretching the hamstring in a concentric and eccentric manner as suggested by Seger et al (1998)[54]. Taking this one step further and applying this information to this review it would be interesting to perform a study which conditions the hamstring muscles in a functional manner by placing the leg in positions seen during running. This might enable the leg to, at a minimum, absorb forces seen during those same positions when actually running. This might inherently decrease the risk of incurring a hamstring injury. An exercise machine
utilizing foot path trajectory to properly place the foot in these strenuous positions would need to be developed.

_Summary_

Properly training an individual to achieve their peak sprinting performance, while also reducing their risk of injury, demands a multifaceted approach involving all aspects of muscular training. Functionally exercising the lower limb as if it were sprinting might help improve lower limb strength in proper proportions. This might also help neuromuscular control of the limb while sprinting which may decrease injury rates and enhance sports specific performances. More research has been called upon to further develop knowledge on each of these respective factors and their relative contribution to hamstring strains. Recommendations have been made to incorporate all of these factors into preventative and rehabilitative strengthening programs.[55, 56] If exercise programs are implemented that positively affect these factors, the probability of an injury occurring or reoccurring might decrease.
Chapter III: Methods

Following extensive review of the literature, it was determined that the trajectory of the foot needs to be examined throughout the entire range of speeds of human locomotion. Considering resources available and other extrinsic factors associated with any clinical study, the following methods were developed to help quantitatively define the trajectory of the foot during the running gait in a laboratory setting. Methods concerning subject categorization, data collection, equipment involved, and analyses undertaken are discussed thoroughly to aid with the replication of this work and discussion of information found.

Subjects

*Inclusion Criteria*

Subjects were considered eligible for the study only if they were athletes 18-40 years of age who participated in a sport requiring significant amount of running at high velocities that lasted at least 10 weeks in duration (i.e. soccer, track, basketball, baseball), who also rated their current level of activity no lower than a 3 and their training intensity level no lower than a B on a modified user activity questionnaire.(Appendix I, Figure A.1) This questionnaire was developed based on similar criteria in participation forms used for gauging intensity and athletic level in individuals. [57, 58]

*Exclusion Criteria*

Individuals were excluded from participation if they had a lower extremity injury within the past year, had a history of surgery to the lower extremity within the last 2 years, answered yes to any question found on the Participation Assessment Questionnaire[59] or did not pass the aforementioned inclusion criteria.
**Screening Questionnaire**

Based on the above inclusion and exclusion criteria, and the goals of this study, a questionnaire was developed to screen and group individuals for later statistical analysis. (Appendix I) Subjects were stratified into 5 categories. Two questions based upon two previously published questionnaires were used to stratify subjects. Question 2 of the questionnaire graded activity level adopted from the participation category of Straub and Hunter’s activity scale.[57] Only individuals rated as a 3 or above were considered. Question 3 was adopted from the Noyes et al. sports activity rating scale.[58] Only individuals of levels A and B were considered for this study.

**Characteristics**

13 males (age=23±4 yrs, weight=78±10 kgf, height=1.80±.06 m, leg length=.973±.048 m) and 13 females (age=23±5 yrs, weight=61±8 kgf, height=1.66±.07 m, leg length=.872±.045 m) participated in this study. Subjects and their characteristics based on stratification parameters of activity level, participation amount and the corresponding measures of age, height, weight and leg length are listed in Table 3.1.
### Table 3.1 Subject Characteristics.

<table>
<thead>
<tr>
<th>Population Bins</th>
<th>Distribution of Subject Parameters (Mean ± St.Dev.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training Status</td>
<td>Activity Level</td>
</tr>
<tr>
<td>Participation Amount</td>
<td>A</td>
</tr>
<tr>
<td>Gender</td>
<td>Male (amount)</td>
</tr>
<tr>
<td>Female (amount)</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5</td>
</tr>
<tr>
<td>Age (yrs.)</td>
<td>20 ± 1</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.79 ± 0.09</td>
</tr>
<tr>
<td>Weight (kgf)</td>
<td>76 ± 16</td>
</tr>
<tr>
<td>Leg Length (m)</td>
<td>0.975 ± 0.078</td>
</tr>
</tbody>
</table>
Procedures

If the potential subject qualified for the study and was willing to participate, a mutually agreeable time was arranged to test at our lab. Subjects were instructed to wear athletic clothing to the testing session. Clothing consisted of athletic shorts, a shirt and the running shoes were provided.

Once the subjects arrived at the lab, they read and signed an IRB approved consent form informing the subject of all the injury risks associated with partaking in this study. (Appendix III) The height of the individual was measured using a wall mounted measure (m). [20] Age (years) and weight (kgf) were also recorded.

Subjects were outfitted with reflective markers to describe their right, lateral side of their lower extremity. Reflective markers were placed on the following locations: the left and right ASIS, sacrum, lateral femur epicondyle, the running shoe at 3 locations: directly posterior to the lateral malleolus (heel), below the lateral malleolus on the lateral side, and the fifth-metatarso-phalangeal. [28] An example of this marker set can be seen in Figure 3.1.
Figure 3.1 Anatomical Marker Setup
Once outfitted with reflective markers, an anatomic static calibration file of the hip was captured to later be used to calculate leg length.[60] Shoes were removed during this procedure to reduce error in the estimated measurement of hip center height with respect to the ground. The treadmill surface was considered a rigidly firm ground compared to the relatively variable shoe intermediate. Once complete, the left ASIS and sacral markers were removed. Subjects then put on the provided shoes and were instructed on proper use of the treadmill and then began walking and jogging until they felt they could effectively sprint. The warm-up session lasted approximately five to ten minutes depending on the individual subject.[19, 61]

After the subject felt that they could adequately sprint if needed, they were instructed that they would have to run at several speeds in an increasing order. Speed order was not randomized due to ethical considerations of the possibility of performing a maximal sprint on a subject’s first trial and incurring an injury.[62] Speed categories were 2, 3.8, 4.52, and 5.36 m/s, respectively. These speed categories covered the spectrum of approximately minimum running speed to the maximum speed of the treadmill being used with 3.8 m/s intentionally being used for comparison of previous published kinematic works.[20] The lower 3 speed categories were collected for 15 seconds while the fastest speed was only collected for 10 seconds. The difference in speed collection duration was implemented due to concern that some subjects would have some difficulty maintaining the fastest speed for the desired time. Collecting for 10 seconds at the fastest speed was shown to produce a similar amount of gait cycles as collecting for 15 seconds at the slower speeds. After each trial, subjects were allowed as
much time as they personally needed to feel recovered before beginning the next trial. In addition to the subject’s personal opinion as to whether they could continue, the subject’s pulse was taken at their wrist during recovery. The subject proceeded to the next speed category only after their heart rate was less than 110 Beats per Minute (BPM)[19] and they had given verbal consent to continue. This rest period typically lasted approximately one minute. After all categories of speed were complete, the subject’s reflective sensors were taken off and the data collection session was concluded. A depiction of a data collection session can be seen below in Figure 3.2. Also shown in this figure is the lab coordinate system to help clarify future discussions involving particular coordinate parameters.
Figure 3.2 Data collection setup and lab coordinate system. Features a subject running on the treadmill during a given running trial.
Data Collection Equipment

The positions of the markers were tracked using a digital motion capture system (Motion Analysis Corporation, Santa Rosa, CA.) A sample rate of 200 Hz was used to capture kinematic data from the reflective markers with the use of four cameras assuring marker accuracy.[62] The treadmill used was for generic home use and speed range was 0 to 5.36 m/s. Treadmill running speed was calibrated using a reflective marker adhered to the revolving treadmill belt during a data collection trial. Being a lower end treadmill model, observations were made prior to data testing on the rigidity of the treadmill for these selected speeds. It was concluded that an assumption could be made that movement from the treadmill was negligible compared other sources of error such as marker placement and would not be improved with a higher end treadmill.

Processing

The camera system was calibrated to capture the lower extremity and done before the subject arrived. Individual subjects were digitized using a 3 second static calibration file which was exported to Visual 3D (C-Motion Inc., Rockville MD) to be used to locate hip joint centers[60] and calculate leg length. Running raw data was exported to Matlab (Mathworks, Natick MA) and Excel (Microsoft Corporation, Redman, WA) for all further analyses. A separate low-pass 4th order Butterworth filter was applied to each reflective marker channel used. A power spectral and subsequent residual analysis was performed to identify the frequencies of noise for each marker and choose the optimal cut-off frequency for filtering.[63] All markers were filtered at 5 Hz with exception to the hip marker which was filtered at 1 Hz for the x-coordinate (length of the treadmill) and y-coordinate (width of the treadmill). This different filtering frequency was needed to
offset undesired instantaneous treadmill translation. This would be necessary to correctly offset coordinate data relative to the hip marker described further in the Calculations section.

**Calculations**

Twelve gait cycles taken from each of the 10-15 second trials. Maximum horizontal position of the femoral epicondyle marker was used to determine the onset of the gait cycle.[28] Data points were parameterized and normalized to 201 points for each gait cycle using a cubic spline interpolation function in Matlab. The ankle marker was chosen to represent foot position and was offset to a constant position relative to the hip marker in order to accommodate for temporal and spatial translation along the treadmill during subsequent gait trials.[28] Trajectory paths and corresponding variations were ensemble averaged from the 12 normalized gait cycles for each subject. Vertical, Horizontal and Depth Foot Displacement ranges were calculated from the processed coordinate data.

**Statistical Analysis**

The dependant measures of FDR for each plane were statistically evaluated using an ANCOVA to determine subject factors that contributed to differences in trajectory. Independent variables considered in this analysis consisted of subject activity level, participation amount, age, height and leg length. Following results of this analysis, subjects were further stratified into quartiles based on the significant contributing factor of leg length for comparison across speeds. Cartesian coordinate data for each quartile was further ensemble averaged amongst subjects within each respective quartile for every speed. These trajectories were graphed to aid in qualitative descriptive analysis. FDR was once again calculated for each strata with mean and variances reported. FDR values
were compared across speeds using pair wise T-tests to identify differences in mean FDR values. Significance was set a priori at $\alpha=.05$. Additional T-tests were performed to evaluate the null hypothesis that depth FDR was zero, meaning the foot did not deviate from the sagittal plane a significant amount.
Chapter IV: Results

Results are divided by hypothesis, which is stated once again for ease of reading. It should be understood that hypotheses II-IV are similar in nature and discussions might tend to overlap. Hypothesis I identifies contributing factors to the foot trajectory and allows us to separate subjects by these factors for comparison to each other. Hypotheses II & III investigate the Horizontal and Vertical dimensions in the sagittal plane and introduce respective graphs to illustrate differences. Presentation of Hypothesis IV is in the same format as II & III but focuses on the third dimension of depth. All four hypotheses are repeated preceding each respective section for ease of reading. Results are first reported verbally then shown in figures when appropriate at the end of each respective section.

**Hypothesis I:** Activity level and running speed will contribute significantly to the differences in trajectory path with large differences in height and leg length contributing slightly. All other factors will contribute insignificantly.

Three, 3-way interactions were found within subject factors. An interaction was found between the parameters of foot displacement range (FDR), speed and activity level. (F=3.325, p=.033); FDR, speed and leg length (F=3.482, p=.028); and similarly, FDR, speed, and sex. (F=2.986, p=.048) A further parameter analysis of pooled subjects revealed that leg length was the most contributing factor to FDR across speeds. For the pooled subjects, leg length was still shown to contribute significantly in the horizontal direction at the two fastest speeds of 4.52 m/s (p=.031) and 5.36 m/s (p=.022), respectfully. Similarly, significance in the vertical direction was found at speeds of 3.8
m/s (p=.031), 4.52 m/s (p=.006) and 5.36 m/s (p=.003), respectfully. No significant contributing factors were found in the depth direction among the different speeds.

Hypothesis II & III: The horizontal and vertical FDR will increase with speed.

With leg length being the most contributing factor to FDR at different speeds, the population was divided into quartiles dependant upon leg length and further analyzed. Furthermore, when FDR was analyzed within subjects’ respective leg length quartiles, both the horizontal and vertical direction FDR means were found to be significantly different among all speeds. (p<.05) These divisions and resultant FDR means can be seen in Table 4.1. When observing Table 4.1 it should be noted the amount of males and females comprising each leg length bin. Males were not represented in the first quartile while females were not represented in the 4th quartile. An equivalent parameter analysis separating the population by gender emphasized the role of leg length as a determining factor in males. A significant three way interaction was found among dimension, speed, and leg length. (F=9.183, p=.048) Leg length contributed significantly in the depth direction for the running speeds of 3.8 m/s (p=.025), 4.52 m/s (p=.014) and 5.36 m/s (p=.027), respectively. No significance was observed in the horizontal and depth directions, however, considering the small sample size of 13 males, it should be noted that p values in the horizontal direction for the last three speeds ranged from .053 to .079. Surprisingly no causative interactions were found when females were isolated despite the noticeable significance observed in the equal sample size of male counterparts.
Table 4.1 Foot Displacement ranges and corresponding Standard Deviations for all speeds grouped according to leg length quartile.

<table>
<thead>
<tr>
<th>Leg Length Quartile</th>
<th>Leg Length (m)</th>
<th># of Subjects</th>
<th>Foot Direction</th>
<th>2</th>
<th>FDR (m) for every Speed (m/s)</th>
<th>3.8</th>
<th>4.52</th>
<th>5.36</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male Female</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>≤ .864</td>
<td>7</td>
<td>Horiz ‡</td>
<td>0.605 ± 0.039</td>
<td>0.849 ± 0.036</td>
<td>0.917 ± 0.048</td>
<td>0.966 ± 0.040</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Depth</td>
<td>0.063 ± 0.015</td>
<td>0.063 ± 0.017</td>
<td>0.070 ± 0.020</td>
<td>0.072 ± 0.021</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vert ‡</td>
<td>0.245 ± 0.020</td>
<td>0.480 ± 0.050</td>
<td>0.543 ± 0.045</td>
<td>0.579 ± 0.049</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>.865-.924</td>
<td>5</td>
<td>Horiz ‡</td>
<td>0.638 ± 0.091</td>
<td>0.844 ± 0.030</td>
<td>0.909 ± 0.047</td>
<td>0.969 ± 0.031</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Depth</td>
<td>0.063 ± 0.036</td>
<td>0.063 ± 0.021</td>
<td>0.070 ± 0.014</td>
<td>0.072 ± 0.010</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vert ‡</td>
<td>0.266 ± 0.055</td>
<td>0.443 ± 0.094</td>
<td>0.521 ± 0.112</td>
<td>0.564 ± 0.104</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>.925-.967</td>
<td>1</td>
<td>Horiz ‡</td>
<td>0.625 ± 0.035</td>
<td>0.900 ± 0.049</td>
<td>0.975 ± 0.049</td>
<td>1.023 ± 0.043</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Depth</td>
<td>0.057 ± 0.021</td>
<td>0.058 ± 0.021</td>
<td>0.061 ± 0.024</td>
<td>0.070 ± 0.027</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vert ‡</td>
<td>0.267 ± 0.043</td>
<td>0.485 ± 0.069</td>
<td>0.537 ± 0.052</td>
<td>0.597 ± 0.051</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>.968+</td>
<td>0</td>
<td>Horiz ‡</td>
<td>0.690 ± 0.083</td>
<td>0.957 ± 0.077</td>
<td>1.038 ± 0.111</td>
<td>1.110 ± 0.117</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Depth</td>
<td>0.057 ± 0.022</td>
<td>0.052 ± 0.018</td>
<td># 0.064 ± 0.011</td>
<td># 0.079 ± 0.018</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vert ‡</td>
<td>0.307 ± 0.077</td>
<td>0.564 ± 0.133</td>
<td>*† 0.625 ± 0.135</td>
<td>*† 0.664 ± 0.120</td>
<td></td>
</tr>
</tbody>
</table>

* Indicates leg length factor contributing significance for entire population (males & females). (p<.05)
† Indicates leg length factor contributing significance for pooled males only. (p<.05)
‡ Indicates mean FDR was significantly different at all speeds for given leg length quartile. (p<.05)
# Indicates mean FDR was significantly different at selected speed only for given leg length quartile. (p<.05)
These results are also graphically represented in Figures 4.1-4.3. Vertical scaling ranges were kept the same in all figures to ease comparison of curve characteristics. An important curve characteristic to observe is seen in both Figures 4.1 and 4.3. All curves represented in these figures are concave down and translated vertically according to corresponding leg length stratification. This indicates increasing FDR with progression of speed at a decreasing rate. Figure 4.2, in contrast, shows linear curves of little to no slope indicating no relationship was seen in the depth direction confirming statistical results.
Figure 4.1 Horizontal Foot Displacement Range over speed grouped by leg length

Horizontal Direction Foot Displacement Range Vs. Speed & Leg Length

- - 1st Quartile —— 2nd Quartile •••• 3rd Quartile — 4th Quartile
Figure 4.2 Depth Foot Displacement Range over speed grouped by leg length
Figure 4.3 Vertical Foot Displacement Range over speed grouped by leg length

Vertical Direction Foot Displacement Range Vs. Speed & Leg Length

- 1st Quartile
- 2nd Quartile
- 3rd Quartile
- 4th Quartile
Ensemble averages of horizontal & vertical Cartesian coordinate data for each leg length bin across speeds can be seen in Figures 4.4-4.7. It should be clear from each figure the obvious encapsulation of each curve as speed progresses. This might indicate similar relationships are seen between subjects of differing leg lengths as shown statistically. Standard deviations were not included on these figures in order to increase ease of reading considering the closed loop nature of these data.
**Figure 4.4** Sagittal plane foot path averages for subjects in the 1st leg length quartile for each speed

Foot Path Ensemble Average Comparisons Over Speed

1st Leg Length Quartile
Figure 4.5 Sagittal plane foot path averages for subjects in the 2nd leg length quartile for each speed

Foot Path Ensemble Average Comparisons Over Speed

2nd Leg Length Quartile

Horizontal Direction (m)

Vertical Direction (m)

- 2 m/s
- 3.8 m/s
- 4.52 m/s
- 5.36 m/s
Figure 4.6 Sagittal plane foot path averages for subjects in the 3rd leg length quartile for each speed.

Foot Path Ensemble Average Comparisons Over Speed
3rd Leg Length Quartile
Figure 4.7 Sagittal plane foot path averages for subjects in the 4th leg length quartile for each speed

Foot Path Ensemble Average Comparisons Over Speed
4th Leg Length Quartile
Hypothesis IV: The depth FDR will decrease with speed.

Although leg length was not shown to be a contributing factor in determining depth FDR, when separated into leg length quartiles, depth FDR was found to be significantly different among subjects in the 4th leg length quartile for all but the slowest speed of 2 m/s. (p<.05, Table 4.1) Despite little statistical findings when trying to correlate depth FDR to any parameters analyzed over different speeds it should not be overlooked the deviation of the foot in the depth direction. The foot was shown to significantly deviate from the plane created by the horizontal and vertical vectors over all speeds for all leg length categories (p<.05) with corresponding average depth direction data reported in Table 4.2. A qualitative example of the three dimensional aspect of the foot during running gait is also demonstrated in Figure 4.8 and 4.9 with a comparison of a single subject’s data taken from the 4th leg length quartile. A single subject was used due to the insignificant findings of relationships within the subject population. The width of the blank space seen in Figure 4.9 demonstrates the foot’s tendency to not remain solely in the vertical/horizontal plane throughout the gait cycle. It should also be observed that for this particular subject, the ratio of foot displacement in the horizontal and vertical direction compared to the depth direction was large reaching upwards to 11.98 and 7.08 at 4.52 m/s, respectively.
Figure 4.8 Frontal Plane Foot Paths for a given subject over all speeds. View is from the rear.
Figure 4.9 Transverse Plane Foot Paths for a given subject over all speeds. The foot path progresses in a counterclockwise fashion throughout the gait cycle. View is from above.
Chapter V: Discussion

The main purpose of this study was to quantitatively describe the three dimensional path of the foot while running at several speeds. Several hypotheses were developed to anticipate what the path of the foot would do in all three dimensions. Since running is an activity in which millions of athletes participate, none the two alike, an additional hypothesis was developed to further investigate the extent to which the factors of height, age, sex, leg length, activity level and participation amount might contribute to the path of the foot during running. Findings are further discussed below and categorized by hypothesis just as in the results section.

Contributions of stride length and subject characteristics

The first hypothesis attempted to describe factors associated with subjects that could accurately predict characteristics which would directly contribute to foot path differences over the speeds seen in this study. As hypothesized, speed was proven to be the greatest determining factor associated with the foot path. This hypothesis was based on previous literature which showed that speed dictated factors such as stride length and stride frequency; both of which are fundamental components of locomotion and undoubtedly components of foot path mechanics.[20, 27, 64] The influence of speed on the running path is further discussed with hypotheses 2-4. After speed was determined to be the most significant variable, other possible subject characteristics had to be evaluated for interactions across speeds.

Not all anticipated outcomes were fulfilled while evaluating this hypothesis. Surprisingly activity was not found to contribute significantly to measured foot path characteristics. This disagrees with Hoshikawa who made the observation that elite
sprinters have distinct running patterns different from those less skilled.[27] Hoshikawa based this conclusion on data collected on Olympic Athletes at higher speeds. The most skilled subjects in this study were NCAA Division I track runners which totaled three. Also considered skilled was a NCAA Division I soccer player. Anecdotally, when observing all subjects’ data, the tallest male track athlete had substantially larger horizontal and vertical FDR. This particular athlete was the closest athlete comparable to Hoshikawa’s subjects. It should also be noticed, however, the running speeds at which data was collected. The fastest speed collected in this study was 5.36 m/s while reported speeds reached by these high caliber athletes can exceed 12 m/s. It is possible that if higher speeds were studied, the same conclusions could be drawn as Hoshikawa. These two distinct limitations are recognized as limitations in this study.

The most counterintuitive finding was that height was shown to not contribute to the characteristics of the foot path. One would think that the taller the person is the longer their stride length would be which then translates to foot path characteristics. For example, one would think that if someone is 20 cm taller than another individual they will naturally have a longer stride length than the other individual and therefore exhibit different foot path mechanics. This might be true in extreme cases, however little evidence suggests that height directly correlates to stride length. The correlation between height and stride length has been examined in several studies.[20, 65, 66] These studies show that there is little to no substantial correlation between height and stride length. These studies used similar measurement techniques as this study, either a wall measure or measure on a weight scale. All subjects were standing when measurement were taken,
just as in this study. These studies did, however, find that leg length had the highest correlation to stride length, which agrees with this study’s results.

Using the above example again, if someone was 20 cm taller than another person, the taller person might more importantly have a different leg length. If so, the foot path characteristics might differ between the two individuals. This study found that there was a significant interaction between leg length, speed and foot path. This is in agreement with previous research.[20, 65, 66] One important factor that should be noted is the method of leg length measurement used in this study. In this study true leg length was calculated indirectly from hip joint center generated using Bell’s method.[60] Leg length discussed in most previous research measures leg length from the greater trochanter to the lateral malleolus. In this study, leg length was measured from the hip joint center to lateral malleolus for one particular reason and that was the three dimensional analysis of this study. Previous studies focused on sagittal plane kinematics while this study included the third depth dimension. If the leg is considered a linkage system as it commonly is in reverse dynamics[63], trochanteric height is irrelevant since the leg rotates about the hip joint center. For comparison to previous research, this is a delimiting factor of this study, however, this author considers the method of leg measurement used to give a better indication of leg length’s role in the calculation of foot path mechanics, especially when the depth dimension is considered. Since this hypothesis failed to be rejected and showed the highest correlation of predicting factors to our dependant variables, the population was grouped into four quartiles according to leg length for all further comparisons. This served as a method of properly grouping subjects for accurate comparisons. This process is not uncommon and has been implemented in
previous research with similar goals as this study; specifically, attempting to differentiate the effect of anthropometric factors of foot path mechanics.[20]

**Horizontal Displacement**

The second hypothesis failed to be rejected as horizontal FDR increased with speed as projected. This was not surprising as previous research has clearly demonstrated that stride length increases with speed ranges covered in this study.[29, 64] With increases in speed and subsequently increases in stride length one should reasonably conclude that the horizontal FDR of the foot during running would increase as speed increased as a result of increases in stride length. That being said, factors such as stride length and leg length are tools at the runner’s disposal to be used to maintain the desired speed. Previous research has shown that for speeds used during this study stride length has been the tool of choice for runner’s to obtain faster speeds.[25] This research has shown that the relationship between stride length and speed is linear until approximately 6 m/s. The top speed in this study was 5.36 m/s, noticeably shy of 6 m/s. Figure 4.1 shows the horizontal FDR for all four leg length classifications. The lower three speeds indicate a linear relationship between speed and horizontal FDR. However, at the fastest speed a linear relationship is not observed. Instead we still see an increase in horizontal FDR with an increase to the fastest speed but this time at a decreasing rate. This indicates that the relationship between speed and horizontal FDR is not solely co-dependent but involve other factors.

If speed and horizontal FDR was solely dependent upon stride length this relationship would have remained linear throughout these relatively slower speeds captured during this study. A possible explanation is the use of stride frequency to
maintain speed at this upper speed. If stride frequency was used to maintain speed rather that stride length, horizontal FDR would only increase as much as stride length and this would have resulted in the foot traversing its running path more quickly while not elongating in the horizontal direction thus maintaining speed. This intuitive explanation does not agree with Sinning (1970)[29] who states that stride frequency does contribute to changes in speed but only at higher speeds than observed in this study. Sinning mentions that that adjustment of stride frequency at these speeds in plausible but not likely. In his conclusion Sinning cites Hugberg (1952)[67] where data for two runners indicated that stride frequency did not contribute to speed significantly until 11.4 m/s. In speeds from 3.9 m/s to 5 m/s stride frequency only increased 1.4%. Similarly, Cavanaugh reported an increase in stride frequency of 4% and stride length 28% when runners increased their speed from 3 m/s to 4 m/s. These data of course have apparent flaws such as subject activity level, population size, and possible collection method discrepancies but for the most part are sound. If, however, stride frequency occurs at a speed that is a percentage of their personnel maximum possible speed, this might account for the differences in findings. Previously mentioned reported data didn’t account for or didn’t provide information regarding the heterogeneous nature of the running population but mainly focused on exceptionally skilled athletes. If this is true, a higher skilled athlete will most likely have a higher maximum speed and thus a higher speed where a frequency transition would be notable. Unfortunately, this present study’s data analysis did not include appropriate calculations to refute or accept any explanations concerning stride length and frequency.
If stride frequency was not adjusted to compensate for a less than optimal stride length, another factor must be accountable for the decreasing rate seen with the horizontal FDR. It should now be mentioned that when evaluating the 1st hypothesis a small interaction was found between speed, FDR, and intensity level. Previous studies have had a relatively homogenous subject pool when evaluating the relationship between stride length and speed. It is possible that by separating subjects by leg length, the intensity level relationship might be seen at the highest speed. This is of course just speculation and further research might be justified to examine this minor discrepancy.

**Vertical Displacement**

Running by definition describes human locomotion as progressing horizontally forward. Most previous works have been concentrated and usually devoted to the description of the horizontal components of running, as it should. If this study was focused on jumping, it would be a different story! The vertical FDR increased with speed as anticipated. This hypothesis was developed and analyzed based on evaluating two areas of work, first foot trajectory and secondly joint kinematics.

In terms of foot trajectory Ivanenko[28] published sagittal plane foot paths during walking at several speeds leading up to the slowest speed in this study. His plots showed a constant qualitative progression of the height of the foot above the floor as speed increased. This study seemed to pick up right where Ivanenko left off with the vertical foot path continuing to elongate with each progression of speed. Data at the higher speeds agreed with similar data reported by Cavanaugh and Hoshikawa. [20, 27] Cavanaugh and Hoshikawa showed foot path plots at several different speeds, these plots were not ideal for comparison and no scale was given, however, despite these less than
ideal conditions for comparison, they gave a good indication of how similar the shapes the foot paths would be at comparable speeds for other subjects.

These results are consistent with the theory of treating the lower limb as a linkage system as mentioned previously. During the swing phase of running the leg undergoes hip flexion coupled with relatively small and constant knee flexion. As speed increases maximal knee flexion also increases. This helps reduce the moment of inertia of the lower extremity about the hip joint consequently decreasing the required hip flexion torque required to reposition the leg for foot contact. In a position of maximal knee flexion, the foot is naturally tucked towards the hip’s center of rotation. This will of course increase the height of the foot off the ground as speed increases as seen in the significant findings of vertical FDRs for all subjects over speed. This of course will have limited results as the foot can only be tucked so high of the ground towards the hip. Vertical elongation should begin to level off as speed is further increased past the speed collected in this study. Once foot height is at a maximum it is reasonable that stride frequency will then begin to increase at the moment of inertia about the leg is now at its smallest possible value and hip flexion can then begin to occur at its fastest possible rate.

**Depth Displacement**

Hypothesis IV was rejected on all accounts. As speed increased it was apparent that the foot did not significantly deviate towards a path that traveled in the plane created by the horizontal and vertical vectors. The variation of the foot path range in the depth direction was great enough to not find any associative factors over speed but it is very important to note that further analysis revealed that the depth FDR was not zero. As obvious as this may seem, this indicates that running is three dimensional. This finding is unique in the
respect that all statements concerning the depth dimension of the foot have been anecdotal and not reinforced statistically. Now that a statement has been made the question should now become how three dimensional? Depth FDRs for all conditions are listed above in Figure 4.1. The depth FDRs range in magnitude between .05 and .07 meters for all conditions. Compare this to both the horizontal FDR which ranges .6 to 1.11 meters and the vertical FDR which ranges .25 to .66 meters, respectively. As speed increased and horizontal and vertical FDRs increased, depth FDR remained the same. The resulting ratios of the horizontal and vertical FDRs to the depth FDR increased over speed and are all substantially greater than one. This relationship should be further investigated into higher speed categories to see if there is any movement away from this constant deviation seen at these relatively slower speeds.

Conclusion
Researchers conducting studies involving the running gait routinely use trajectories of the lower limbs to help make sense and properly analyze the dependant measures they are concerned with. Surprisingly, little information has actually been reported on the trajectory of these limbs which is so commonly used as an unreported tool for analysis. This study was intentioned to provide quantitative data to describe a movement component that is regularly observed and assumptions drawn upon but hardly ever empirically reported on.

It is our opinion that this study has elaborated on and provided a descriptive basis for several topics concerning running. Some results found that should be highlighted include the finding that leg length is a major factor in determining the characteristics of the foot trajectory opposed to the commonly held belief that height is
predictive. This was in agreement with previous research and helped substantiate some of the methods used during this study concerning leg length measurement which did differ slightly from previous research. Three dimensional aspects of running were also visited which has not been done. Sagittal plane findings agreed with previous research while the third dimension was somewhat surprising. We found that the foot slightly deviates from the sagittal plane but its tendencies are not dependant upon the subject parameters we currently measured. This is helpful because it shows us that running is actually a three dimensional movement but its third dimension component is small and might be difficult to control for.

This study has attempted to continue where walking gait studies have stopped, the transition from walk to run. Due to limiting factors, this study reached speeds at the transition from run to sprint. A study concerning speeds greater than the present top speeds upwards as to maximum speed would completely describe the trajectory of the foot for all locomotive speeds and should be undertaken.
Chapter VI: Summary

Functional training for running is a promising concept which has the potential benefits of improving performance and possibly reducing injuries. A review of the literature highlighted the apparent need to further investigate the trajectory of the foot in order to properly design methods to functionally train an individual for running. A data collection procedure was used to quantify foot trajectory for several speeds on a treadmill. Speeds used during this study could be classified as a jog to a fast run. Two specific hypotheses were generated and answered in this research project:

1. What effect does speed have on the end point trajectory of the foot during running?
2. What effect do the factors of height, age, leg length, sex, activity level and participation amount have on predicting the end point trajectory of the foot during running.

Analyses were in agreement with previous literature that has mainly focused on the relationship of speed and other dependant variables such as stride length, stride frequency, joint kinematics and anthropometric variables. The range of the foot for all subjects increased both horizontally and vertically while depth remained relatively constant and greater than zero as speed increased. An ANCOVA showed that leg length was found to be the most meaningful factor in determining the characteristics of foot trajectory over speed. With leg length significantly contributing to the dependant measure of trajectory, the subject population was divided into quartiles based on their leg length and their trajectory further analyzed within these groups over speed. This information can especially be used in the design of a device to replicate certain aspects of running.
Recommendations for Future Research

Methods developed in this study should further be applied to investigate the foot path nearing maximal speeds. If such a study is undertaken, conclusions can be drawn concerning the three dimensional trajectory of the foot over the entire spectrum of locomotion.

It is usually the goal of researchers to replicate outside environments in a laboratory. Ideally, future studies should eliminate some of the present limitations such as the use of a treadmill to represent overground running as this can greatly limit the inference of laboratory results to actual circumstance.

Foot trajectory envelopes found in this study may give clinicians and researchers an essential tool to further investigate questions concerning specificity training in a controlled running environment, particularly injury prevention to muscle strains of the lower leg and performance enhancement. More than five decades ago, it was necessary for Dempster to investigate the range of motion of the upper extremity to obtain the information necessary to properly design of pilot cockpits.[69] The underlying purpose of this study was to gather information on the trajectory of the foot during running in order better understand the fundamental details of this movement with the goal of one day replicating it. Similar to Dempster, knowledge gained of these trajectory tendencies will be a fundamental tool in the proper design of a device that can replicate the running movement and become a basis for an entire branch of research.
Appendices

Appendix I  Participant Evaluation Form

Please answer the following 7 questions

1. Does the sport you are currently participating in last at least 10 consecutive weeks and involve a large amount of running?
   - Yes
   - No

2. Please check the box that best describes your current level of activity in the sport/s you participate in that involves a large amount of running.
   - Level 1. Professional, Intercollegiate
   - Level 2. Competitive* League (Regular organized training or coaching outside of competition)
   - Level 3. Competitive* Intramural League (Self trained outside of competition)
   - Level 4. Non-Competitive Intramural League (Low intensity, wide range of skills, CO-ED)
   - Level 5. All levels of running exercise, little to no sport application

* Competitive is defined as the level of play amongst players being relatively equal and at a raised intensity

3. Please check one box below that best describes the amount of time during the week that your train above 50% intensity for your sport.
   - Level A 4-7 days/week
   - Level B 2-3 days/week
   - Level C Less than or equal to 1 day/week

4. Please give us a brief description of your current typical training regimen
5. Briefly describe your training history concerning running for your sport

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

6. Have you ever had surgery or experienced a major injury to your lower body (such as a broken bone or torn ligament) that has affected your running?

☐ Yes     If yes, please explain:_________________________________________________

☐ No

________________________________________________________________________

7. Have you been injured within the past year that might have affected your running?

☐ Yes     If yes, please explain:_________________________________________________

☐ No
Appendix II  Physical Activity Readiness Questionnaire

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly. Check YES or NO.

<table>
<thead>
<tr>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>☐</td>
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<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>
| ☐   | ☐  | 7. Do you know of any other reason why you should not do physical activity?
Appendix III Approved IRB consent form.

Consent to Participate in a Research Study

Documenting the trajectory of the foot during the running gait: A quantitative assessment

WHY ARE YOU BEING INVITED TO TAKE PART IN THIS RESEARCH?

You are being invited to take part in a research study about studying the foot trajectory of athletes at several running speeds. You are being invited to take part in this research study because you are a healthy individual between the ages of 18 and 40 years with no history of surgery to the lower extremity, have not been injured in the lower extremity in the past year and are considered to be a serious running athlete. If you volunteer to take part in this study, you will be one of about 40 people to do so.

WHO IS DOING THE STUDY?

The person in charge of this study is Tom Cunningham (PI) of The University of Kentucky’s Kinesiology & Health Promotion department. He is being guided in this research by Timothy Uhl, ATC, PT, PhD. There may be other people on the research team assisting at different times during the study.

WHAT IS THE PURPOSE OF THIS STUDY?

The purpose of this study is to analyze the effect that several factors such as height, training status and speed have on the path of the foot while running on a treadmill at several speeds. By doing this study, we hope to investigate methods for accurately describing the path of the foot in three-dimensions. This study might help investigators form future research questions concerning the development of an exercise machine which might help improve running performance and reduce injury risk.

WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST?

The research procedures will be conducted at The University of Kentucky Musculoskeletal Laboratory in the Charles T. Wethington Building. You will need to come to the Musculoskeletal Lab 1 time during the study. The visit will take about 1.5 Hour. The total amount of time you will be asked to volunteer for this study is 1.5 hours over the next day.
WHAT WILL YOU BE ASKED TO DO?

You will be asked to fill out an activity rating scale form as well as a brief medical assessment for exercise. Once complete, your height and weight will then be recorded.

You will be given a pair of athletic shoes and asked to complete a warm-up routine of treadmill walking and jogging, stretching and cycling until you feel you can effectively sprint. The warm-up routine should last approximately ten to twenty minutes. To ensure your safety, prior to using the treadmill, instructions of proper use of the treadmill will be explained to you. You may ask questions at any time. These instructions will be as follows:

**Starting the Treadmill**

1. Before the treadmill is turned on, stand with a foot on each foot rail located on opposite sides of the treadmill
2. When the treadmill is initially turned on, use the handrails to your sides to maintain your balance without stepping on the treadmill.
3. The treadmill will start at its lowest speed, 1 mile per hour. When you are ready you may begin walking on the treadmill.

**Data Collection and Warm-up**

4. **DO NOT OPERATE THE CONTROLS YOURSELF. THE INVESTIGATOR HELPING YOU WILL DO SO FOR YOU. AN EXCEPTION TO THIS IS THE EMERGENCY SHUT OFF CORD. YOU SHOULD PULL THIS CORD ANYTIME YOU FEEL YOU MIGHT BE AT RISK FOR INJURY.**
5. For your warm up routine, you can tell the instructor to go faster or slower as desired and they will adjust the controls.
6. Do not dismount the treadmill while the belt is moving unless you feel you must to avoid injury.

**Stopping the Treadmill**

7. At the end of each trial or at the end of the warm-up routine the treadmill will be brought to a gradual stop. **DO NOT DISMOUNT THE TREADMILL UNTIL INSTRUCTED.**
8. Once the treadmill has stopped. You will be instructed to stand in the same position as you started.

Seven reflective markers will be placed on your body at several locations to help us identify your hip, foot and thigh. The marker locations can be explained to you in more detail if you would like.
After you have adequately warmed-up, you will be asked to run at 4 speeds whose order will be performed in an increasing order. You will run at; 2, 3.8, 4.52, and 5.36 meters per second, respectively. If you are unfamiliar with the units of meters per second and how fast this is, the table below might be helpful for you to gage the speeds.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Speed (m/s)</th>
<th>Speed (MPH)</th>
<th>Mile Time (Min:Sec)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>4.5</td>
<td>13:20</td>
<td>Fast Jog/Slow Run</td>
</tr>
<tr>
<td>2</td>
<td>3.8</td>
<td>8.5</td>
<td>7:04</td>
<td>Distance Run</td>
</tr>
<tr>
<td>3</td>
<td>4.52</td>
<td>10.1</td>
<td>5:56</td>
<td>Fast Run</td>
</tr>
<tr>
<td>4</td>
<td>5.36</td>
<td>12</td>
<td>5:00</td>
<td>Approaching Sprint</td>
</tr>
</tbody>
</table>

These speeds cover the entire range of running speeds of the treadmill being used. Each speed category will be collected for 10-15 seconds. Time will be provided between trials for you to be fully recovered before doing the next trial. An investigator will make sure you are not fatigued by measuring your heart rate. The investigator will do this by placing two fingers on your wrist and counting your pulse. Once your heart rate is under 110 beats per minute (BPM) you can then complete the next trial when you are ready. After all categories of speed are complete, the markers will be taken off and the data collection session will be over. The entire session should last about 1.5 hours.

**ARE THERE REASONS WHY YOU SHOULD NOT TAKE PART IN THIS STUDY?**

You will not be able to participate if you are under the age of 18 or over the age of 40, don’t fit the inclusion criteria concerning your activity level, have had surgery to your lower extremity or have incurred an injury to your lower extremity within the past year. You should not participate in this study if you have any concerns as to whether you can perform at the mentioned running speeds safely.

**WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?**

You have been offered the opportunity to participate since you are a runner in your regular recreational activities. Although this confirms your preparedness, muscle cramps, muscle fatigue, dizziness, orthopedic injury (strains and sprains), cardiorespiratory distress and even death are all possible outcomes of any high intensity physical activity, including that required for this study. However, in this monitored situation, the risks are lower than when exercising at this level on your own.

There is always a chance that any physical activity can harm you, and the activity in this study is no different. We will do everything we can to keep you from being harmed. In addition to the risks listed above, you may experience a previously unknown risk or side effect.
WILL YOU BENEFIT FROM TAKING PART IN THIS STUDY?

You will not get any personal benefit from taking part in this study.

DO YOU HAVE TO TAKE PART IN THE STUDY?

If you decide to take part in the study, it should be because you really want to volunteer. You will not lose any benefits or rights you would normally have if you choose not to volunteer. You can stop at any time during the study and still keep the benefits and rights you had before volunteering.

IF YOU DON’T WANT TO TAKE PART IN THE STUDY, ARE THERE OTHER CHOICES?

If you do not want to be in the study, there are no other choices except not to take part in the study.

WHAT WILL IT COST YOU TO PARTICIPATE?

There is no cost to you for participating in the study.

WHO WILL SEE THE INFORMATION THAT YOU GIVE?

We will keep confidential all research records that identify you to the extent allowed by law.

Your information will be combined with information from other people taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. You will not be identified in these written materials. We may publish the results of this study; however, we will keep your name and other identifying information confidential.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. For example, your name will be kept separate from the information you give, and these two things will be stored in different places under lock and key. You should know, however, that there are some circumstances in which we may have to show your information to other people. For example, the law may require us to show your information to a court.

CAN YOUR TAKING PART IN THE STUDY END EARLY?

If you decide to take part in the study you still have the right to decide at any time that you no longer want to continue. You will not be treated differently if you decide to stop taking part in the study.
The individuals conducting the study may need to withdraw you from the study. This may occur if you are not able to follow the directions they give you, if they find that your being in the study is more risk than benefit to you, or if the agency funding the study decides to stop the study early for a variety of scientific reasons.

WHAT HAPPENS IF YOU GET HURT OR SICK DURING THE STUDY?

If you believe you are hurt or if you get sick because of something that is due to the study, you should call Tom Cunningham at 517-902-1545 or the faculty advisor, Timothy Uhl, PhD. at (859) 323-1100 ext. 80858 immediately. We will determine what type of treatment, if any, that is best for you at that time.

It is important for you to understand that the University of Kentucky does not have funds set aside to pay for the cost of any care or treatment that might be necessary because you get hurt or sick while taking part in this study. Also, the University of Kentucky will not pay for any wages you may lose if you are harmed by this study.

Medical costs that result from research related harm can not be included as regular medical costs. Therefore, the medical costs related to your care and treatment because of research related harm will be your responsibility; your insurer may agree to pay those costs (you should ask your insurer if you have any questions regarding your insurer’s willingness to pay under these circumstances); Medicare, or Medicaid will pay medically necessary costs (if you have any questions regarding Medicare/Medicaid coverage you should contact Medicare by calling 1-800-Medicare (1-800-633-4227) or Medicaid 1-800-635-2570.

A co-payment/deductible from you may be required by your insurer or Medicare/Medicaid even if your insurer or Medicare/Medicaid has agreed to pay the costs).

If you are eligible for Veterans Affairs medical benefits, the VA provides medical care if you get hurt or get sick as a result of taking part in this study. The necessary care must be provided in a VA medical facility unless an exception is granted. In cases of exceptions, the VAMC Director may contract for such care. Exceptions include: situations where a VA facility is not capable of furnishing economical care, situations where a VA facility is not capable of furnishing the care or services required and situations involving a non-veteran research subject. The VA does not provide medical treatment for a research-related injury in cases where injuries result from noncompliance by a research subject with study procedures.

A co-payment from you may be required for medical care and services provided by the VA.

WHAT IF YOU HAVE QUESTIONS, SUGGESTIONS, CONCERNS, OR COMPLAINTS?

Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions, suggestions,
concerns, or complaints about the study, you can contact the investigator Tom Cunningham at (517) 902-1545 or the faculty advisor Timothy Uhl at 859-323-1100 ext. 80858. If you have any questions about your rights as a volunteer in this research, contact the staff in the Office of Research Integrity at the University of Kentucky at 859-257-9428 or toll free at 1-866-400-9428. We will give you a signed copy of this consent form to take with you.

**WHAT ELSE DO YOU NEED TO KNOW?**

You will be told if any new information is learned which may affect your condition or influence your willingness to continue taking part in this study.

_____________________________________________  
Signature of person agreeing to take part in the study  
_________________________  
Date

_____________________________________________  
Printed name of person agreeing to take part in the study  
_________________________  
Date

_____________________________________________  
Name of [authorized] person obtaining informed consent  
_________________________  
Date

_____________________________________________  
Signature of Investigator
References


Vita

Thomas J. Cunningham

Date of Birth: June 23, 1982
Place of Birth: Louisville, Kentucky

Education

B. S. University of Kentucky, College of Engineering

- Major: Mechanical Engineering

Professional Experience

President and founder of TC Motions Inc. 2006-present

Graduate research assistant, University of Kentucky. 2005-present

Mechanical Engineering Internship, Lexmark International. 2003-2006