RELATIONSHIP BETWEEN CHANGES IN FOOT STRIKE PATTERN AND INDICES OF FATIGUE IN A MAXIMAL 800-METER RUN

A Thesis
by
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Abstract

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Background: Several studies have considered biomechanical differences between rearfoot (RF) and forefoot (FF) strike pattern during running. These differences include muscle activation, ground contact times, and ground reaction forces. It has been suggested that the FF strike pattern is utilized more by faster runners and for quicker running. During a marathon, it has been shown that foot strike pattern (FSP) changes during the course of a race. During faster, shorter distances, such as an 800-m middle distance, it is unclear whether runners are able to maintain a FF strike pattern. Given the high intensity of the race, it is likely that onset of muscle fatigue would make it difficult for runners to maintain a FF strike throughout the race. **Purpose:** The purpose of this study was to evaluate changes in FSP throughout a maximal 800-m run. We hypothesized that runners would shift from a more FF to a more RF striking pattern during the race as measured in 100-m intervals. In addition, these changes in FSP would be related to muscle activity. **Methods:** Twenty-one subjects (14 female, 7 male; age: 23.86 ± 4.25 yrs) were recruited for this study from the surrounding area and university. Subjects completed a maximal effort 800-m run while FSP and muscle activity of the tibialis anterior (TA) and lateral gastrocnemius (LG) were assessed. To evaluate FSP, 3-dimensional accelerometer data was used to determine resultant acceleration peaks which coincide with foot strike. Two measures of FSP, foot strike initial angular velocity ($\omega_{\text{FS-ave}}$) and change in foot angle $\Delta\theta_{\text{ave}}$), were then calculated based off sagittal plane gyroscope data for each foot strike and were averaged across each 100-m interval. Step peak and step average EMG values ($TA_{\text{MEAN-ave}}$, $LG_{\text{MEAN-ave}}$, $TA_{\text{PEAK-ave}}$, $LG_{\text{PEAK-ave}}$) associated with each foot strike were calculated and averaged across each 100-m interval of the 800-m run. Two-way repeated measure analyses of variance (ANOVA) were used to analyze split times, $\omega_{\text{FS-ave}}$ and $\Delta\theta_{\text{ave}}$, and $TA_{\text{MEAN-ave}}$, $LG_{\text{MEAN-ave}}$, $TA_{\text{PEAK-ave}}$, $LG_{\text{PEAK-ave}}$ across each 100-meter interval separated into curve and straight intervals. Pearson-product moment correlations were performed between FSP and EMG measures, as well as FSP measures and final time. **Results:** The main results showed there was a significant increase in split times throughout the 800-meter run (F [3, 60] = 15.188, $p < 0.001$). There were significant differences seen between curves and straight intervals for $\omega_{\text{FS-ave}}$ (F [1, 20] = 21.707, $p<0.001$) and $\Delta\theta_{\text{ave}}$ (F [1, 20] = 18.445, $p<0.001$). In addition, significant negative correlations were observed between $LG_{\text{MEAN-ave}}$, and $LG_{\text{PEAK-ave}}$ with $\omega_{\text{FS-ave}}$ and $\Delta\theta_{\text{ave}}$ ($p<0.001$), meaning more FF strike was correlated with more LG muscle activity. **Conclusion:** FSP did not change throughout the 800-m run, with subjects remaining in a more FF strike position; however, there were significant differences in FSP between straight intervals and curve intervals, where subjects employed a more FF strike on the curve intervals compared to straight intervals.

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Dedication

For My Parents and My Nana—Thank You for Everything

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CHAPTER 1: INTRODUCTION

BACKGROUND

There has recently been an increase in research related to different foot strike patterns during running and how they affect performance and efficiency (Di Michele & Merni, 2014; Kasmer, Wren, & Hoffman, 2014; Ogueta-Alday, RodríGuez-Marroyo, & GarcíA-LóPez, 2014; Perl, Daoud, & Lieberman, 2012). In general, there are three foot strike patterns: a rear foot (RF) strike, in which the heel of the foot is the first to make contact with the ground; a mid-foot (MF) strike, in which the middle of the foot hits the ground first; and a forefoot (FF) strike, in which the ball of the foot hits the ground first and the heel rarely, if ever, touches the ground (Hasegawa, Yamauchi, & Kraemer, 2007). There are many biomechanical differences between a RF and FF strike pattern including ground contact time and muscle activation (Cavanagh & Lafortune, 1980; Hasegawa, Yamauchi, & Kraemer, 2007; Hayes & Caplan, 2012; Landreneau, Watts, Heitzman, & Childers, 2014).

First, RF running has been associated with greater ground contact times than FF running (Di Michele & Merni, 2014; Hasegawa et al., 2007; Hayes & Caplan, 2012; Ogueta-Alday et al., 2014). It has been observed that during sprinting and faster running, a more FF strike is employed (Hasegawa et al., 2007; Kasmer et al., 2014; Novacheck, 1998). This has been observed in races as long as a marathon, where the top runners were more likely to employ a FF running style (Hasegawa et al., 2007), and also in sprinting, where elite sprinters perform with a FF strike (Novacheck, 1998). Adrigo et al (1995) concluded a FF strike may be a better choice for sprinters and middle distance runners to attain higher speeds. In FF running, the gastrocnemii muscles are activated earlier and longer than RF strikers (Ahn et al., 2014). In addition, significantly less activity is seen in the tibialis anterior in FF strikers compared with RF strikers (Landreneau et al., 2014). The earlier activation of the gastrocnemii muscles could increase elastic energy storage capacity and lead to increased force output of the plantarflexors during the stance phase of running (Roberts, 2002).

It has been proposed that fatigue of the muscles surrounding the ankle and lower extremity could be the cause of the inability to maintain a FF running style for a prolonged (15-20 minutes up to a marathon) run (Jewell, Boyer, & Hamill, 2017; Larson et al., 2011). It has been observed that a FF running style may not be maintainable for the entirety of a run, ranging from 15 minutes to a marathon (Jewell et al., 2017; Larson et al., 2011). There have been multiple studies in which a hard running effort is employed to induce fatigue in the lower extremity muscles (Bates, Osternig, & James, 1977; Elliot & Ackland, 1981; Elliot & Roberts, 1980; Gefen, 2002; Mizrahi, Verbitsky, & Isakov, 2000; Paavolainen, Nummela, Rusko, & Hakkinen, 1999). The results have shown that fatigue is associated with a decrease in the ability of the musculoskeletal system to reduce shock waves from ground contact, an increase in muscular activity, an increase in ground contact time, a reduction in the ability to sustain muscular force and control of joints, a decrease in peak and vertical ground reaction forces, a reduction in stride length, and a decrease in dorsiflexion at heel contact (Bates et al., 1977; Elliot & Ackland, 1981; Elliot & Roberts, 1980; Gefen, 2002; Mizrahi et al., 2000; Nummela, Rusko, & Mero, 1994; Nummela, Vuorimaa, & Rusko, 1992; Paavolainen et al., 1999, 1999). Although there appears to be a general idea of fatigue effects in running, there have been few studies to date in which a short, very intense running effort is used to induce fatigue.

Of the studies that have looked at short to middle distance races, various biomechanical changes have been observed. For example, Bates et al (1977) filmed subjects during a 400-

meter race and found a significant reduction in velocity throughout the race caused by a shortening of step length, a reduction in knee drive, and changes in the ability of the limbs to attain the same range of motion by the end of the race. In a 3000-meter race, decreases in stride length, increases in ground contact time, and a less perpendicular shank angle upon ground contact (producing a deceleration effect) have been observed (Elliot & Roberts, 1980). In a study of 800- and 1500-meter races, Hayes and Caplan (2012) found a larger percentage of runners utilized a FF or MF strike (31 and 42 percent) than in longer distance races, such as the marathon, where it is has been observed close to 75 percent of runners using a RF strike pattern (Hasegawa et al., 2007). Hayes and Caplan (2012) did not monitor changes in strike pattern over the course of the races, however a significant increase in ground contact time was found on the second lap of the race compared to the first lap, which could be indicative of a shift to striking more posteriorly on the foot. In addition, a decrease in velocity throughout the race was observed (Hayes & Caplan, 2012). Although these studies have looked at biomechanical changes in a race setting, recent advancements in technology allow the ability to assess more direct changes, rather than through only videography or cumbersome equipment.

STATEMENT OF THE PROBLEM

Several studies have attempted to assess the effects of fatigue on kinematic changes during a long run or exhaustive protocol (Bates et al., 1977; Elliot & Ackland, 1981; Elliot & Roberts, 1980; García-Pinillos, Soto-Hermoso, & Latorre-Román, 2016; Gefen, 2002; Hasegawa et al., 2007; Hayes & Caplan, 2012; Jewell et al., 2017; Kasmer et al., 2014; Larson et al., 2011; Mizrahi et al., 2000; Nicol, Komi, & Marconnet, 1991; Paavolainen et al., 1999). Many studies in which the kinematic and kinetic variables associated with running were studied have been performed on a treadmill to enable easier data collection and control. However, it is known that treadmill running is not the same as running over ground (Nigg, De Boer, & Fisher, 1995). This is especially true in shorter races, such as the 400 or 800-meter run, where there are many slight pace adjustments that cannot be accounted for on a treadmill (Hanon & Thomas, 2011). Therefore, it is important to assess changes during running over ground. Previously, there has been a lack of technology to enable data collection running over ground, with the only methods of analysis being stationary cameras offering a single shot at one time point.

There appears to be a lack of empirical evidence in short duration race efforts where kinematic and muscle activity variables have been assessed during the activity. In addition, there have been no studies to date in which these variables have been gauged during an 800-meter run done on an actual track surface. Finally, the effects that fatigue may have on the inability to maintain a FF strike pattern are still unknown. Therefore, the purpose of this study was to evaluate the possible biomechanical changes that occur during a maximal 800-meter run and their relationship to changes in foot strike in runners. The participants completed a race effort 800-meter run on a track while electromyography (EMG) of selected muscles of the lower leg, lactate, and changes in foot strike pattern throughout the run were assessed. Lactate was measured in order to determine fatigue induced by the run because lactate has been shown to be one of the most well-known biomarkers of muscle fatigue (Finsterer, 2012).

HYPOTHESES

During the maximal 800-meter run, it was hypothesized that:

Hypothesis 1: There will be a shift from a more FF to a more RF striking pattern during the race as measured in 100-meter intervals.

Hypothesis 2: Better performance will be correlated with the percentage of time spent in a FF strike.

Hypothesis 3: Fatigue measures (lactate, step peak EMG, step average EMG) will be related to changes in foot strike pattern.

SIGNIFICANCE OF THE STUDY

This study will help determine if there is a shift in FSP and reasons for this change. Elucidating the reasons for a shift in foot strike will be beneficial for training. For example, if evidence is found that one of the reasons for shifting foot strike is an increase in plantarflexor activity and ability to generate force, steps can be taken during training to increase endurance of that muscle and making it less prone to fatigue. Additionally, the use of newly available technology could enable the ability to track small changes in performance.

CHAPTER 2: REVIEW OF LITERATURE

INTRODUCTION

The emphasis of running research has shifted from that of metabolic to biomechanics in order to determine the most efficient, economical, and fastest way to run. Although there has been much research as to the effects that fatigue has on kinematic and kinetic variables during running, there is little research on these variables during a race effort 800-meter run. In addition, many protocols that have been done to evaluate changes in kinematic and kinetic variables with fatigue have been done on treadmills. Although running on a treadmill for research purposes makes data collection easier and eliminates many confounding variables, treadmill running is not the same as over ground running (Nigg et al., 1995). For this reason, it was determined to be important to look at changes in biomechanical variables when running on an actual track. This became especially true when looking at the 800-meter run due to its complex nature of racing in which small pace changes cannot be accounted for on a treadmill (Hanon & Thomas, 2011).

The inability to maintain a certain foot strike pattern throughout a fatiguing event may be detrimental to performance. For this reason, finding a cause for the change in foot strike pattern could be beneficial for making training adjustments and potentially lead to better performance. This review of literature will be aimed at looking at the way humans run, the different foot strike patterns that exist, and the differences between these patterns. In addition, the effects that fatigue has on running biomechanics will be elucidated.

THE GAIT CYCLE

The gait cycle begins when one foot encounters the ground and ends when the same foot comes into contact with the ground again. The stance phase, where the foot is in contact with the ground, ends when the foot leaves the ground. The running gait is characterized by two periods of double float at the beginning and end of the swing phase, where neither foot is touching the ground. The swing phase is initiated by toe-off, which occurs before 50% of the gait cycle is completed. The timing of toe-off is dependent upon speed, where faster running allows for less time to be spent in the stance phase, making toe-off occur somewhere between 35 and 40% of the gait cycle. During sprinting, toe-off can occur as early as 22% of the gait cycle (Novacheck, 1998). The gait cycle is depicted in Figure 1 below.

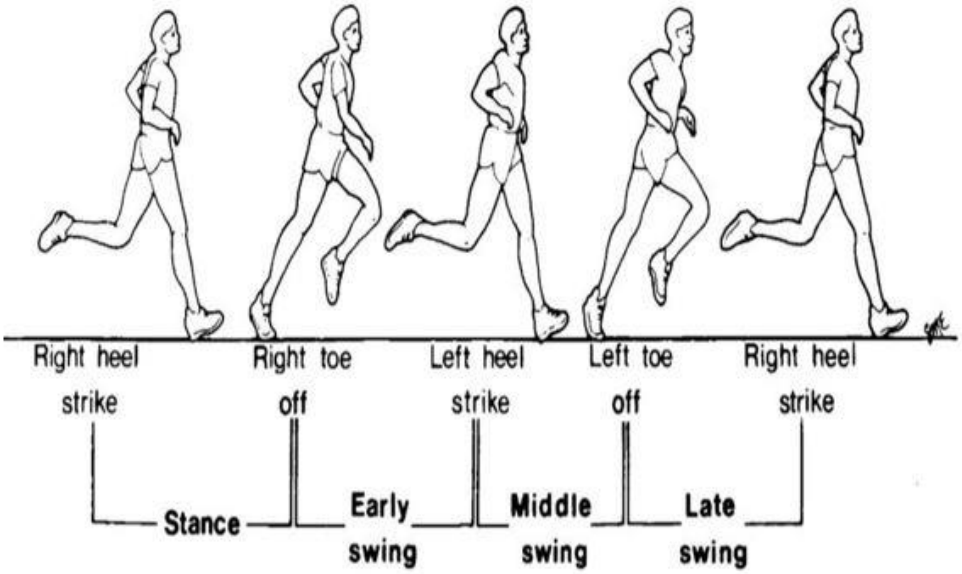

Figure 1. (From Reber, et al, 1993) Phases of running.

During running at all speeds, periods of absorption and generation and periods of deceleration and acceleration occur (Novacheck, 1998). During absorption, the body's center of mass falls from its peak height reached during the double float. This occurs from the start of swing phase to initial contact. After initial contact, absorption continues through part of the stance phase. Once the center of mass reaches a certain point in stance phase, there is a shift to generation. The center of mass is propelled upward and forward during this part of the stance phase and allows the limb to be propelled into swing phase after toe-off (Novacheck, 1998). The periods of absorption and generation and the phases of the running cycle they occur in are depicted in Figures 2 and 3 below.

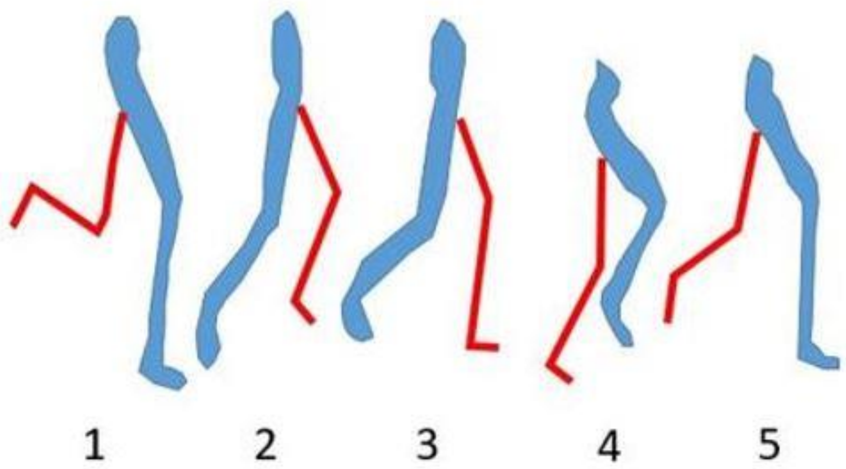

Figure 2. (Adapted from Novacheck, 1998) The gait cycle. 1. Stance phase absorption. 2. Stance phase generation. 3. Swing phase generation. 4. Swing phase reversal. 5. Swing phase absorption. The blue leg signifies the leg of interest.

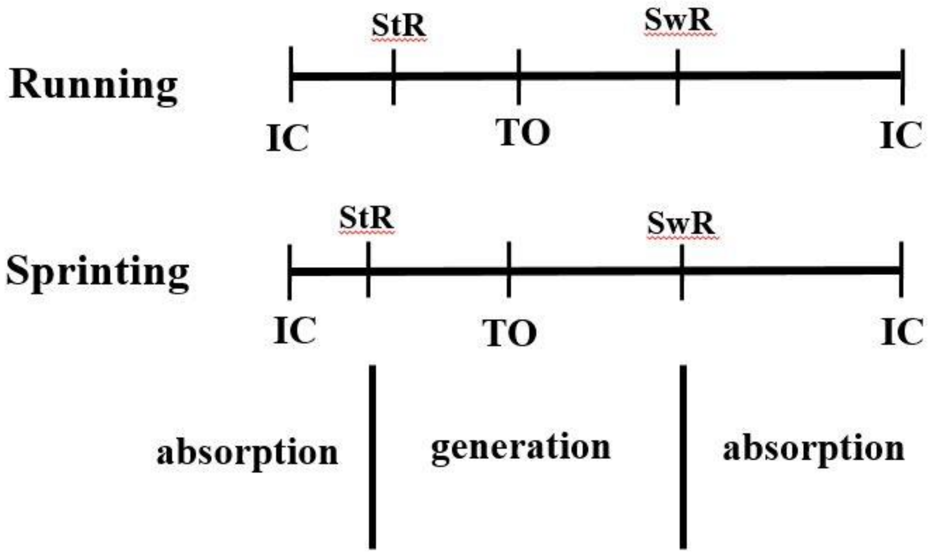

Figure 3. (Adapted from Novacheck, 1998) The running gait cycle. IC, initial contact; TO, toe off; StR, stance phase reversal; SwR, swing phase reversal; absorption, from SwR through IC to StR; generation, from StR through TO to SwR.

FOOT STRIKE PATTERNS

Typically, there are three foot strike patterns seen in human running—rear foot strike (RF), in which the heel, or rear third part of the sole, is the first part of the foot to make contact with the ground; a mid-foot (MF) strike, in which the middle of the foot, or the entire sole, is the first to make contact with the ground; and a forefoot (FF) strike, in which the forefoot, or front half of the sole, is the first to make contact with the ground and the heel rarely, if ever, makes contact with the ground (Hasegawa et al., 2007). It should be noted, however, that the foot strike pattern exists across a continuum, and not everyone falls into these rigid categories (Cavanagh & Lafortune, 1980). The foot strike patterns are depicted in Figure 4 below.

Figure 4. (From Hasegawa et al, 2007) Sample picture of foot strike patterns. Rear foot strike, mid-foot strike, and forefoot strike.

It has been observed that a RF strike is overwhelmingly the most common among runners, with reports of the prevalence of RF strikers being above 75% (de Almeida, Saragiotto, Yamato, & Lopes, 2015; Hasegawa et al., 2007). RF strike prevalence is followed by a MF strike, and only a small percentage of runners employ a FF strike, comprising less than 2% (Hasegawa et al., 2007). However, these numbers may be somewhat skewed because most observations are taken from a longer distance race, such as the marathon, so runners in short events, such as the 800-meter or mile, may have a greater majority of FF strikers (Hayes & Caplan, 2012). In a study of 800-meter and 1500-meter races looking at ground contact characteristics, Hayes and Caplan (2012) found that 31% of runners were FF strikers, 42% were MF strikers, and only 27% were RF strikers. As speed increases, initial foot contact with ground changes from the RF to the FF, where elite sprinters may never touch their RF to the ground (Novacheck, 1998).

With many faster runners employing a FF strike pattern, it has been suggested that the FF strike pattern is more economical, however, this may not be the case (Hasegawa et al., 2007). Ogueta-Alday and colleagues (2014) found habitual RF striking runners are more economical than MF striking runners. Williams and Cavanagh (1987) suggested that RF runners may be more economical because the RF pattern allows the shoe to help absorb some of the impact shock upon ground contact (Williams & Cavanagh, 1987). When FF runners do not utilize the cushioning of the shoe to absorb impact shock, more energy must be used by muscular contraction to absorb the shock, and therefore increase metabolic cost. Kram and Taylor (1990) stated the energy cost of running relative to body weight is inversely proportional to the rate of force application. By using ground contact time as a measure of force application, where FF runners have shorter ground contact times, the authors state reducing ground contact time would increase oxygen cost, making the runner less economic. Perl et al (2012) compared subjects who ran habitually in minimal shoes or barefoot during FF and RF striking wearing minimal or standard shoes. The authors found runners were 2.41% more economical in the minimal shoe condition than standard shoe when running with a FF strike pattern. The runners were 3.32% more economical when running with the RF strike pattern in minimal shoes than in the standard shoe. However, there were no significant differences found between RF and FF running in either condition (Perl et al., 2012). Other studies have also found no significant differences in O_2 consumption when comparing FF and RF strikers (Adrigo et al., 1995; Cunningham, Schilling, Anders, & Carrier, 2010; Gruber, Umberger, Braun, & Hamill, 2013). With varying results, it is hard to determine if one foot strike is more economical than the other. The reason that many faster runners may use a FF pattern is for the decrease in ground contact time, which in turn allows them to run at a faster velocity. RF runners consistently show greater ground contact time than FF runners (Di Michele & Merni, 2014; Hasegawa et al., 2007; Hayes & Caplan, 2012; Ogueta-Alday et al., 2014). Adrigo et al (1995) concluded a FF strike may be a better choice for sprinters and middle distance runners to attain higher speeds.

Although running economy is an important aspect to running performance, carbohydrate oxidation is a limiting factor in endurance exercise, and thus may also be important to running performance (Coyle, Coggan, Hemmert, & Ivy, 1986). Gruber, Umberger, Braun, and Hamill (2013) studied habitual RF and FF runners and the differences between these groups when running with their habitual strike pattern and an alternative strike pattern. The authors found carbohydrate oxidation was greater in FF runners than RF runners (Gruber et al., 2013). This could suggest running with a RF strike pattern may conserve intramuscular glycogen stores and allow for an endurance run to be sustained longer (Gruber et al., 2013).

There are a number of biomechanical differences present when looking at RF and FF strike patterns. FF strikers activate the medial and lateral gasctrocnemii muscles earlier and longer (Ahn et al., 2014). It has been proposed that earlier activation of the gastrocnemii muscles increases the elastic energy storage capacity of the elastic tissues by stretching the Achilles tendon before landing and, therefore, leads to increased force output of the plantarflexors during the stance phase of running (Roberts, 2002). There is significantly less activity in the tibialis anterior and greater activity in the medial head of the gastrocnemius in FF strikers (Landreneau et al., 2014). When looking at the foot contact during RF running, the ankle is dorsiflexed, allowing the heel to make first contact with the ground (Williams & Cavanagh, 1987). The opposite is seen in FF runners, where the foot lands in a significantly more plantarflexed position, allowing the FF to reach the ground first (Landreneau et al., 2014; Williams & Cavanagh, 1987). Running with a FF strike requires the plantar flexor muscles to contract eccentrically at ground contact and act as a shock absorber when the foot makes contact with the ground (Laughton et al., 2003; Williams III et al., 2000). Because the initial plantar flexion angle causes higher levels of peak and average plantar flexion values, higher levels of strain on the plantar flexor muscles could be present in FF runners (Pohl & Buckley, 2008). Echoing these findings, Kulmala et al (2013) stated that running with a FF strike pattern increases ankle contribution by causing higher plantarflexor moments and Achilles tendon strain compared with a RF strike pattern. Landing in a more plantarflexed position puts additional strain on the triceps surae (the soleus and gastrocnemius muscles attaching to the Achilles tendon) muscles (Sinclair et al., 2016). It has been suggested running with a FF strike pattern could allow for more elastic energy storage (Perl et al., 2012). A FF strike pattern allows for more controlled dorsiflexion and could allow for more elastic energy storage and return (Hof, Van Zandwijk, & Bobbert, 2002; Perl et al., 2012). The heel descends under this controlled dorsiflexion and allows for a greater stretch of the Achilles tendon while the triceps surae contracts eccentrically (Hof et al., 2002; Perl et al., 2012). This greater stretch would allow for more elastic energy storage. In addition, there is the possibility that increasing the contribution of the ankle during FF strike running could lower eccentric quadriceps work during the braking phase of the running gait compared with a RF strike (Kulmala et al., 2013).

There are also differences seen in ground reaction forces (GRF) between the strike patterns. In RF runners, the vertical ground reaction force (vGRF) curve exhibits two peaks: an initial impact peak (passive peak) and the active peak (Cavanagh & Lafortune, 1980). Conversely, FF runners only exhibit an active peak (Cavanagh & Lafortune, 1980). MF and FF strikers demonstrate lower vertical ground reaction force impact peaks and reduced vertical ground reaction force loading rate (Cavanagh & Lafortune, 1980; Laughton et al., 2003). However, the overall peak magnitude of the active peak has been shown to be higher in FF runners compared to RF (Laughton et al., 2003). Loading rate, the slope of the line leading up to the impact peak, has been shown to be higher in RF strikers than FF strikers (Laughton et al., 2003).

MUSCLES USED DURING RUNNING

In human locomotion, many muscles, joints, and tendons enable a fluid motion of the running movement. Running is similar to bouncing on a pogo stick in that when each leg strikes the ground, kinetic and gravitational potential energy are converted to elastic strain energy in the muscles, tendons, and ligaments enabling the energy to nearly all be recovered during the propulsive second half of the stance phase (Cappellini, 2006). The contact phase of running represents the point where force production occurs and where the stretch-shortening cycle action for the leg extensor muscles occurs, which is imperative to force output (Cavagna, Heglund, & Taylor, 1977; Komi, 2000). The majority of muscles are most active in anticipation (pre-activity) of and just after the initial ground contact (Novacheck, 1998). At higher running speeds, there appears to be greater pre-activity of the muscles (Komi, Gollhofer, Schmidtbleicher, & Frick, 1987). Running is a whole-body activity, involving coordinated movement and contribution from muscles in the arms and shoulders, torso, core, hips, lower leg, and foot muscles. For the purposes of this review, focus will be on the on the gastrocnemius and tibialis anterior because these muscles have been most widely studied when looking at the effects of fatigue on foot strike (Jewell et al., 2017). The gastrocnemius and soleus are the main plantarflexors of the foot. Peak activity of the gastrocnemius and soleus occurs during early to mid-stance (Reber, Perry, & Pink, 1993). The tibialis anterior acts to dorsiflex the foot as well as perform inversion of the ankle. In a study by Reber et al (1993), the tibialis anterior showed the highest rate of sustained activity of the five muscles of the lower leg that were studied during running. The authors postulate the tibialis anterior muscle may be more likely to have fatigue-related problems during prolonged running than other muscles due to its high activity throughout the run (Reber et al., 1993).

ELASTIC ENERGY STORAGE AND THE STRETCH-SHORTEN CYCLE

The stretch-shorten cycle (SSC) is characterized by an eccentric muscular contraction, a stretch, followed immediately by a concentric muscular contraction (Harrison, Keane, &

Coglan, 2004). Performing a stretch before the concentric contraction allows for the generation of greater force production and power output (Bosco, Tarkka, & Komi, 1982). The SSC is important for running performance. It has been estimated that without contributions from the SSC, VO_2 would be 30-40% higher during running (Cavagna, Dusman, & Margaria, 1968). During running, gravitational potential energy and kinetic energy are stored in the form of elastic energy during the first half of stance and this elastic energy is returned during the second half of stance (Stearne et al., 2016). The return of elastic energy reduces the metabolic cost of running by allowing the body to not have to use more active tissue to propel the body forward and upward (Stearne et al., 2016). Recently, there has been evidence to suggest that the arch of the foot is the main energy saving structure during running (Ker, Bennett, Bibby, Kester, & Alexander, 1987; Stearne et al., 2016). Ker et al (1987) estimated that approximately 17% of the mechanical work of running could be stored and returned by the foot’s arch as it undergoes compression and recoil during the stance phase of running. The Achilles tendon is also a major energy storing structure (Alexander, 1991). It has been estimated the Achilles tendon stores and returns 35% of the kinetic and potential energy during running (Ker et al., 1987).

Running requires many foot contacts with the ground, giving the opportunity for the return of a substantial amount of energy through the SSC. However, it has been shown that with repeated, fatiguing SSC activities, the contractile ability of the muscle can be decreased (Gollhofer, Komi, Miyashita, & Aura, 1987). This SSC mechanism for energy return could be reduced over time or at high intensities. With fatigue, there is often an increase in ground contact time during running (Hayes, Bowen, & Davies, 2004). More time spent on the ground will affect the coupling phase of the SSC. It is important to keep this phase of the cycle short to achieve the greatest power output. If the coupling phase lasts too long, the elastic energy stored will be lost as heat and the stretch reflex will not allow for enhanced force production during the concentric phase (Bosco, Komi, & Ito, 1981). In a study looking at countermovement and squat jumps to coupling time on end force production, greater coupling time led to a decrease in force output. This would indicate that a longer time spent in the coupling phase will reduce force potentiation (Bosco et al., 1981). Therefore, with fatigue, there is the possibility that increased ground contact time will lead to a loss in SSC capabilities.

FACTORS ASSOCIATED WITH FATIGUE

Exercise induced muscle fatigue is defined as a reversible loss of muscle force (contractility) during work over time (Finsterer, 2012). As fatigue arises during running, many biomechanical and metabolic changes occur. With increases in fatigue, changes can be seen in metabolic pathways, muscle activity, force and shock attenuation, ground contact time, stride length and rate, and foot strike pattern and angle.

METABOLIC SYSTEM

In the 800-meter run, there is contribution from both the aerobic and anaerobic energy systems. Spencer and Gastin (2001) reported a 66% contribution from the aerobic energy system during an 800-meter run, with the crossover to the aerobic energy system occurring between 15- and 30-seconds.

There has been debate over the predominating energy system during the 800-meter run due to the nature of the race. The 800-meter run is most successfully performed by running faster in the beginning of the race and decreasing running velocity by the end of the race (Thomas et al., 2005). Because the race is run in this manner, some people have been led to believe that the anaerobic energy system provides the majority of the energy contribution. Studies have shown anywhere from a 66% contribution of the anaerobic system to 19% during the 800-meter run (Duffield, Dawson, & Goodman, 2005; Hill, 1999; Lacour, Bouvat, & Barthelemy, 1990)**.** The differences between these varying percentages can be seen in protocol differences where some have been done on the treadmill and others over ground. In addition, estimation of anaerobic contributions by extrapolating results from a treadmill test by some authors may have caused an underestimation of anaerobic cost (Duffield et al., 2005). Subtle pace adjustments made throughout the 800-meter race are hard to achieve on the treadmill. These pace adjustments make a difference in how the 800-meter is run and the ability to achieve a race-effort performance on a treadmill becomes difficult. This could account for the underestimation of anaerobic cost made by some authors (Duffield et al., 2005). Taken together, it appears that the aerobic system provides the majority of the energy contribution during the 800-meter run, but the anaerobic system remains important.

With this in mind, in cases in which the energy producing aerobic processes are not able to meet the energy demands of the body, the production of ATP shifts from these aerobic processes to anaerobic glycolysis. As exercise intensity and duration increases, the ADP:ATP ratio decreases due to excessive ATP consumption and the inability to rid the body efficiently of lactate. This will cause a decrease in muscle pH due to the inability to efficiently rid the body of lactate. Muscle pH interferes with cross-bridge binding due to competitive binding. Cross-bridge attachment is reduced during fatigue, which will slow down the process of muscle contraction. A biomarker is a measurable product or substance of an organism that is used as an indicator of a biological state to objectively measure physiological or pathogenic processes in the body that occur during health, disease, or in response to pharmacological treatment (Finsterer, 2012). Biomarkers of muscular fatigue are classified according to the mechanism of fatigue, where biomarkers of muscular fatigue are different for exercise lasting twenty seconds and exercise lasting more than one minute. An area for classification of biomarkers is ATP metabolism. Therefore, one of the most well-known biomarkers of muscle fatigue from ATP metabolism is serum lactate (Finsterer, 2012).

MUSCLE ACTIVITY

Fatiguing bouts of running have shown varying effects on muscular activity (Gefen, 2002; Jewell et al., 2017; Mizrahi et al., 2000; Nicol et al., 1991; Nummela et al., 1994, 1992; Paavolainen et al., 1999). Nicol et al (1991) studied EMG values of the gastrocnemius before and after a marathon. The results revealed the gastrocnemius muscle presented higher integrated EMG values in the braking and propulsive phases, indicative of decreased tolerance at impact and a need to compensate for the loss of elastic recoil. In a study by Nummela et al (1994), an increase in average EMG was found during a 400-meter run using trained 400-meter runners. The authors postulated that the increase in EMG activity during the 400-meter run is caused by an increase in the firing rate and/or recruitment of additional motor units to compensate for failure of contractile properties in the previously recruited muscle fibers (Nummela et al., 1994). In a previous study by Nummela et al (1992), a 23-24% increase in EMG was found during the 400-meter run. In this study, it was concluded fatigue in the 400-meter run is mainly due to processes within skeletal muscle, rather than the central nervous system (Nummela et al., 1992).

In contrast, Jewell et al (2017) found a decrease in integrated EMG values for the lateral and medial heads of the gastrocnemius after a fatiguing 15- to 20-minute run. Similarly, Mizrahi et al (2000) also found a significant decrease in integrated EMG activity of the tibialis anterior, but found no significant change in the gastrocnemius. Bates et al (1977) observed a reduction in knee drive in 400-meter runners at the end of their race and believed that the external manifestation of fatigue during this activity was the result of a decrease in the subject’s ability to generate sustained muscular force. In a 5000-meter time trial, Nummela et al (2006) observed a decrease in EMG activity. The authors also saw a reduction in velocity throughout the run and believed the decrease in muscle activity could be attributed to the subjects slowing down throughout the run. Gefen et al (2002) found that in fatigued conditions, reduced muscular control of the foot-shank joints could impair the ability of these joints to resist eversion or inversion.

GROUND REACTION FORCE

During running, ground reaction forces may reach two-and-a-half to three times an individual’s body weight. The necessity for the muscles, tendons, and joints to absorb this impact is essential in order to prevent injury and continue to run efficiently. With fatigue, changes occur in the body’s ability to both produce and absorb force at ground contact and push-off. At foot strike, the body undergoes shock waves from the impact with the ground. Mizrahi and Voloshin (2000) found fatigue reduces the ability of the musculoskeletal system to attenuate the shock waves from foot strike. After a marathon, there has been shown to be a decrease in the ability of the body to reduce impact force (Komi et al., 1987; Nicol et al., 1991). Similarly, Mercer, Bates, Dufek, and Hreljac (2003) found a 12% decrease in shock attenuation after a graded exercise test. Paavolainen and Nummela (1999) found significant decreases in peak and vertical ground reaction forces after 10,000 meters of running. The authors believe this suggests a large number of repetitive stretch loads during the 10,000-

meter run decreased the capacity of the neuromuscular system to generate force rapidly and tolerate impact forces (Paavolainen et al., 1999).

GROUND CONTACT TIME

With fatigue, an increase in ground contact time has been observed over a wide range of distances. An increase in ground contact time after 10,000-meters of running compared to the start of the race has been observed (Elliot & Ackland, 1981; Paavolainen et al., 1999). As mentioned previously, this increase in ground contact time may alter the ability of the storage of elastic energy in the SSC to be utilized. In looking at 800- and 1500-meter races, Hayes and Caplan (2012) found ground contact on the first lap was significantly shorter than ground contact on the last lap of the race. Contact time has also been shown to increase in half-marathon to ultra-marathon distance events (Hasegawa et al., 2007; Nicol et al., 1991). In addition, fatiguing protocols of longer length (30 minutes) have produced increases in ground contact time (Jewell et al., 2017). Taken together, these results suggest an increase in ground contact time with fatigue regardless of the distance of the run.

STRIDE LENGTH AND RATE

Bates et al (1977) analyzed the effects of fatigue on 400-meter running variables. The authors found a reduction in step velocity which was associated with a shortening of step length, not step frequency (Bates et al., 1977). Elliot and Ackland (1981) found a reduction in stride length throughout a 10,000-meter run, but no changes in stride rate. In another study by Elliot and Roberts (1980) where subjects kept a constant speed throughout a 3,000-meter run, stride length also decreased, but stride rate increased. The differences between these two studies findings for stride rate can be attributed to the velocity of the run. The runners in the

10,000-meter run showed a decrease in velocity, while those in the 3,000-meter run kept a constant velocity throughout the run, causing them to increase their stride rate.

FOOT STRIKE

In runners who are habitual MF or FF runners, there appears to be a shift from the FF running style to landing more posteriorly on the foot throughout a fatiguing run or race. Jewell et al (2017) found significant changes in landing mechanics of habitual FF runners after a 15- to 20-minute fatiguing run that indicate a transition towards more MF strike pattern. Similarly, it has been observed during check points of long distance races (marathons and ultramarathons) that the percentage of FF runners declines, with many switching to a more posterior landing (Larson et al., 2011). Elliot and Ackland (1981) found throughout a 10,000-meter race, there tends to be a decrease in the relative backwards velocity of the ankle at foot strike, creating a greater likelihood of a RF strike.

Jewell et al (2017) found an increase in dorsiflexion at foot contact and a decrease in ankle plantar flexor torque after a fatiguing run. Christina, White, and Gilchrist (2001) performed a fatiguing protocol of the dorsiflexor muscles. In contrast to Jewell and colleagues (2017), Christina et al (2001) found significant decreases in dorsiflexion at heel contact. Both the foot and ankle angles at heel contact decreased following fatiguing exercises, causing the foot to land in a more plantarflexed position (Christina et al., 2001).

With switches from FF to more RF strike patterns being observed, there appears to be an inability to maintain a FF strike pattern for a prolonged period of time. It is unknown why there is an inability to maintain a FF running style. It has been speculated that ankle plantar muscle fatigue could be a contributing factor (Jewell et al., 2017). Another hypothesis is the reduction in elastic energy recoil from the SSC (Kyröläinen, Belli, & Komi, 2001).

THE USE OF ACCELEROMETERS AND INERTIAL MEASUREMENT UNITS IN DETERMINING FOOT STRIKE PATTERNS

Many studies use some type of video analysis to determine changes in foot strike patterns (Ahn et al., 2014; Bates et al., 1977; Di Michele & Merni, 2014; García-Pinillos et al., 2016; Hasegawa et al., 2007; Hayes & Caplan, 2012; Kasmer, Liu, Roberts, & Valadao, 2013; Kasmer et al., 2014; Ker et al., 1987; Kulmala et al., 2013; Landreneau et al., 2014; Larson et al., 2011; Nicol et al., 1991; Perl et al., 2012). This method is limited to gathering data where high-speed cameras have been set up, leading to a small snap shot of data that is gathered from the entire run. Force platforms, force plate instrumented treadmills, and plantar pressure insoles have also been used to assess foot strike changes throughout a run (Jewell et al., 2017; Madigan & Pidcoe, 2003; Mann, Moran, & Dougherty, 1986; Pohl & Buckley, 2008; Verkerke, Ament, Wierenga, & Rakhorst, 1998; Wiegerinck et al., 2009). However, these methods are limited to laboratory settings or require cumbersome equipment to be worn by the subjects. The use of accelerometers in determining gait and foot strike patterns allows for unrestricted movement of the subjects due to small size and wireless capabilities of the system. Accelerometers allow for the examination of segmental accelerations during walking and running and are based on Newton’s 2nd law of motion (F=ma) (Kavanagh & Menz, 2008).

Various researchers have used accelerometers for determining changes in gait during walking and running (Bötzel, Marti, Rodríguez, Plate, & Vicente, 2016; Boutaayamou et al., 2015; Laughton et al., 2003; Moon et al., 2017; Purcell, Channells, James, & Barrett, 2005; Sinclair, Hobbs, Protheroe, Edmundson, & Greenhalgh, 2013). Boutaayamou et al (2015) validated the use of accelerometers in detecting heel strike, toe strike, heel-off, and toe-off during the running gait against the conventional 3D analysis system. The authors found using wireless accelerometers applied to the right and left foot could accurately and precisely detect these events in the gait cycle (Boutaayamou et al., 2015). Similarly, Giandolini et al (2014) compared the use of accelerometers placed on the heel and metatarsal with 2D video analysis to determine foot strike patterns. The authors compared the time between heel and metatarsal accelerations and foot strike angle obtained from the video analysis. The method was determined to be reliable for a wide range of speeds, slopes, and foot strikes (Giandolini et al., 2014). Shank-mounted accelerometers may also be used to accurately and reliably detect gait events (Sinclair et al., 2013). Purcell at el (2005) performed a validation study of accelerometer use in determining ground contact time. The authors found that close estimates of contact time during running were able to be obtained using a shank-mounted accelerometer (Purcell et al., 2005).

Recently, there has been the development of a wireless, skin-mounted, and conformal inertial sensor (BioStampRC, MC10 Inc.) that has the ability to capture gyroscope, accelerometer, and EMG data. Moon et al (2017) evaluated the accuracy and precision of this sensor in measuring gait kinematics in multiple sclerosis patients. The authors found the sensor was able to accurately and precisely measure the number of strides, stride time, swing time, and step time in these patients across different walking impairment levels (Moon et al., 2017). A similar type of sensor has also been used to determine foot strike patterns (Shiang et al., 2016a). Shiang et al (2016a) attached two inertial sensors to the dorsal side of both shoes to identify strike patterns and compared this method to using a 3D motion analysis system. The authors found that both signals showed highly correlated changes (r=0.98) in different strike patterns (Shiang et al., 2016a).

SUMMARY

The running gait is characterized by periods of absorption and generation, where the phase of propulsion is very important for running. This period of force generation can be potentiated by the SSC, in which stored elastic energy is utilized and allows for a reduction in active force production. This reduction in active force production can allow for reduced work of the metabolic system and enable better running economy and performance. Several studies have looked into the effect of fatigue on kinetic and kinematic variables during prolonged bouts of running (Elliot & Ackland, 1981; Elliot & Roberts, 1980; Jewell et al., 2017). Research has shown that there may be an inability to maintain a FF running style with fatiguing exercise (Hasegawa et al., 2007; Kasmer et al., 2014; Larson et al., 2011). Previous studies have observed changes in foot strike during a race, but have not evaluated other biomechanical parameters during the race or found reasons for a shift in foot strike (Hasegawa et al., 2007; Hayes & Caplan, 2012; Kasmer et al., 2014). There have been no studies to date in which kinematic variables have been collected during a short, fatiguing race effort on an actual track. For these reasons, the purpose of this study was to assess the possible biomechanical changes that occur during a maximal 800-meter run and their relationship to changes in foot strike in runners.

CHAPTER 3: METHODS

INTRODUCTION/ EXPERIMENTAL DESIGN

The purpose of this study was to assess the potential biomechanical changes that occur during a maximal 800-meter run and their relationship to changes in foot strike in runners. We hypothesized over the course of the 800-meter run:

Hypothesis 1: There will be a shift from a more FF strike to a more RF striking pattern during the run.

Hypothesis 2: Better performance will be correlated with the percentage of time spent in a FF strike.

Hypothesis 3: Fatigue measures (lactate and EMG) will be related to changes in foot strike pattern.

The independent variables for this study include distance (divided into eight 100-meter intervals) and muscles (lateral gastrocnemius and tibialis anterior). The dependent variables for this study include time, foot angle, foot angular velocity, step average EMG, step peak EMG, and lactate.

PARTICIPANTS

Twenty-one runners (recreational and collegiate) were recruited for this study from the surrounding area running clubs, running community, and University cross country and track teams. They were healthy men (7) and women (14) (no injuries in the past 3-months, no diabetes, cardiovascular, or renal/kidney disease) of the ages 18-35 (Riebe et al., 2015). Subject characteristics are provided in Table 1. The subjects had to be running at least 10 miles per week and be capable of running an 800-m race in under four minutes. Participants completed the 2015 American College of Sports Medicine Exercise Pre-participation Health

Screening Form and provided informed consent approved by the Appalachian State University Institutional Review Board (IRB). The participants had to be cleared for vigorous activity in order to participate in this study.

Subject Characteristics	
Age	23.86 ± 4.25 yrs
Height	171.73 ± 10.09 cm
Weight	63.09 ± 9.92 kg
Average Miles per Week	35.36 ± 19.17 miles

Table 1. Subject characteristics (mean ± standard deviation).

EXPERIMENTAL SETUP

All data collection occurred on a standard 400-meter outdoor track. The subjects completed the running protocol on the outdoor track. The race was performed in the counterclockwise direction beginning at the start of a curve in order to simulate a race environment.

INSTRUMENTATION ASSESSMENT

FSP was assessed by means of BiostampRC sensors (mc10, Lexington, MA, USA). These sensors are lightweight, soft and flexible and were placed on the dorsal surface of the foot underneath the shoe and sock of the right foot. The sensor contains a 3-dimensional accelerometer (± 16 G) and 3-dimensional gyroscope (± 2000°/s). Data are stored in on-board memory. To evaluate FSP, accelerometer and gyroscope data from the foot mounted sensor were used to define two separate measures (see Data Processing). The sensor was attached with a double-sided sticker pressed firmly onto the skin. Accelerometer and gyroscope data were sampled at 250 Hz.

Muscle activation was also assessed by means of BiostampRC sensors (mc10, Lexington, MA, USA), which, in addition to gyroscope and accelerometers, has electrodes to measure electric biopotential (Common-mode rejection ratio (CMRR): -95 dB; input impedance: 5 Ω; gain: 12 (21.6 dB)). EMG data was collected for two different muscles: lateral head of the gastrocnemius (LG) and tibialis anterior (TA). These muscles were chosen as they have been studied previously when looking at foot strike changes and are primary plantarflexors and dorsiflexors of the ankle (Jewell et al., 2017; Mizrahi et al., 2000; Nicol et al., 1991). The sensors that were used to collect EMG data were placed on the muscles according to the SENIAM Project Guidelines (Hermens, 1999). For LG, the sensor was placed at 1/3 of the line between the head of the fibula and the heel and in the direction of this line. The sensor for the TA was placed at 1/3 of the line between the tip of the fibula and the tip of the medial malleolus and in the direction of this line. The surfaces were shaved, abraded, and cleaned with an alcohol swab. These two sensors were attached with a sticker applied to the sensor and pressed onto the skin. These were then secured with cohesive tape to ensure no movement. The EMG data was sampled at 1000 Hz.

LACTATE

Lactate measurements were taken immediately prior to the beginning of the 800-meter run and within 30-seconds following the conclusion of the run to better help estimate the effects of fatigue. The lactate measure consisted of a finger prick and lactate strip analyzer (Lactate Plus, Nova Biomedical, Waltham, MA). The finger was cleaned with an alcohol swab prior to the sample being taken. The lactate analyzer was calibrated using two control solutions prior to each testing session.

EXPERIMENTAL PROTOCOL

Each participant was advised of the protocol and potential risks before selecting a time and date for testing. Upon arrival to the track, the participant was given an informed consent form and an exercise risk assessment questionnaire to complete. Additionally, the subject completed a training information form. Age, height, weight, and weekly mileage information was collected from the subjects.

The subject was allowed time to warm-up on the outdoor track or surrounding area. The warm up was left up to the subject's discretion based on how they normally warm up, but was asked to warm up for a minimum of five minutes, but not more than 15 minutes. Following the warm-up, the subject was instrumented with all BiostampRC sensors. An initial blood lactate concentration sample was taken before the start of the 800-meter run. Immediately before beginning the run, the subject was asked to stand still for three-seconds, perform three jumps into the air, and stand still for another three seconds in order to synchronize timing, FSP, and EMG data.

The subject was then instructed to run the 800-meter as if it were a race. An 800-meter around the outdoor track consists of two laps. The subjects' time was given to them every 200-meters and verbal encouragement was provided. Time for every 100-meters was recorded using a TC Timing System (Brower Timing Systems, Salt Lake City, Utah, USA) with timing gates set up at each 100-meter mark. Additionally, time for every 100-meters was recorded on a stopwatch. Due to the timing gate system not collecting all splits for all subjects, further data analyses were performed the stopwatch time data. The subjects were given a three-command start (on your mark, set, go) to start the 800-meter run. Upon completion of the 800-meter run, a post-800 blood lactate sample was collected within 30-seconds.

DATA PROCESSING

All data was downloaded and processed via custom MATLAB code (Mathworks, Inc., Natick, MA). To measure FSP, 3-dimensional accelerometer data was used to first determine resultant acceleration peaks which coincides with foot strike (Shiang et al., 2016b). To quantify changes in FSP, FSP was evaluated on a continuum, instead of as a binary classifier (RF or FF). Two measures were calculated:

1. Foot strike initial angular velocity (ω_{FS}) — Sagittal plane gyroscope angular velocity over the first 30 ms after foot strike was averaged to get an indication of direction of angular rotation directly after foot contact, with a more positive ω_{FS} indicating a more RF strike pattern (Fig. 5).
2. Change in foot angle ($\Delta\theta$) – Sagittal plane gyroscope data was integrated to get a change in foot strike angle. The difference in angle at foot strike and angle when the foot was deemed to be stationary on the ground (lowest mean resultant acceleration over a 50 ms interval after foot strike) was used to calculate a change in foot angle, with more positive $\Delta\theta$ indicating a more RF strike pattern (Fig. 5):

$$\boldsymbol{\Delta\theta = \theta_{STATIONARY} - \theta_{FOOTSTRIKE}}$$

ω_{FS} and $\Delta\theta$ values for each foot strike were averaged across each 100-m interval ($\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$).

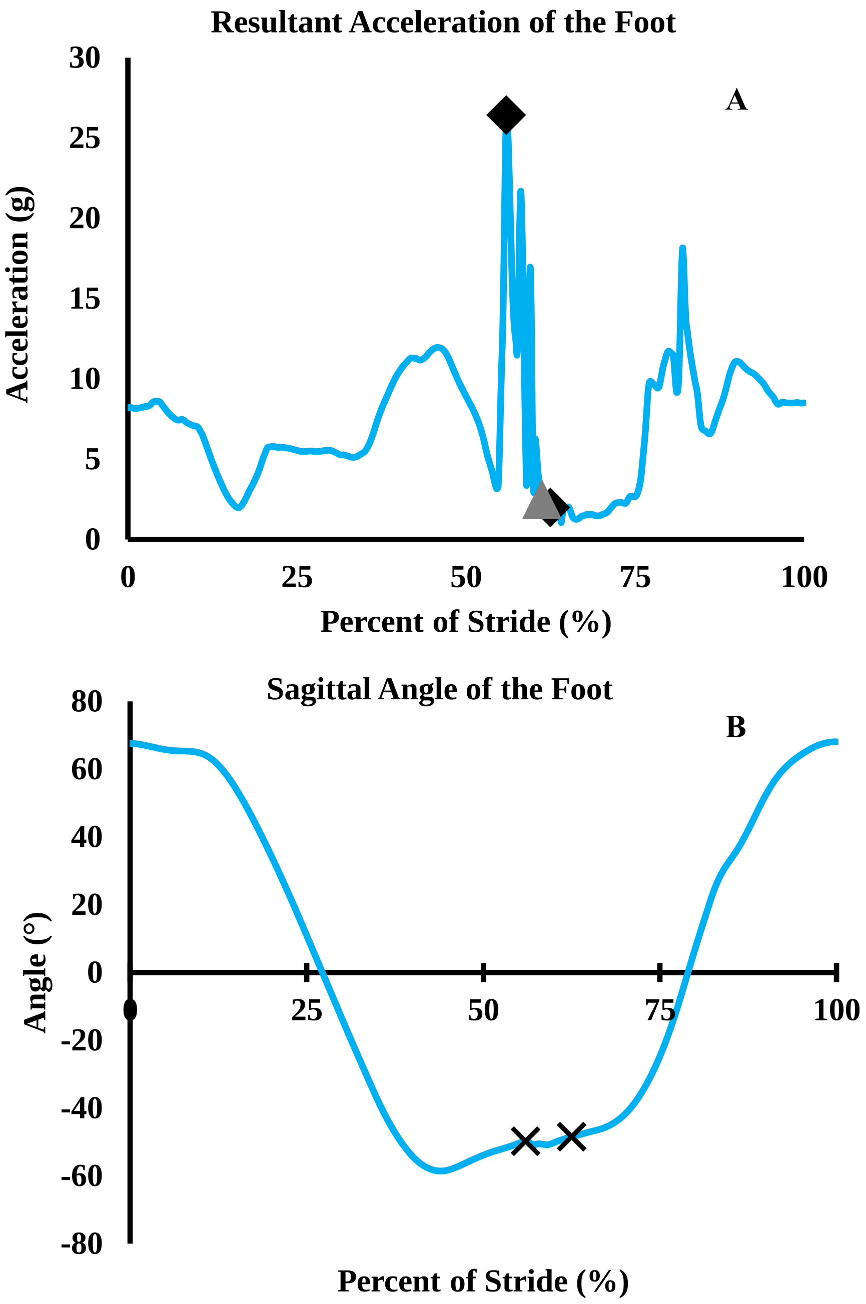

Figure 5. A: Sagittal angle of the foot beginning at the initial swing phase. ✕'s signify angle of the foot at ground contact (1st) and angle of the foot when stationary (2nd). **Figure 5.B**: Resultant acceleration of the foot through a stride. Peak resultant acceleration at foot strike (1st ♦), point 30 ms after foot strike (to determine ω_{FS}) (▲), resultant acceleration at start of stationary foot (to determine $\Delta\theta_{ave}$) (2nd ♦).

EMG data were band-pass filtered (20-400 Hz) and full wave rectified before a linear envelope (low-pass filter at 10 Hz) was employed. Step peak and step average EMG values ($TA_{MEAN\text{-}ave}$, $LG_{MEAN\text{-}ave}$, $TA_{PEAK\text{-}ave}$, $LG_{PEAK\text{-}ave}$) associated with each foot strike were calculated and averaged across each 100-m interval of the 800-m run. Additionally, all FSP measures and EMG measures were analyzed during the straight and curve intervals of the 800-meter run.

STATISTICAL ANALYSIS

A two-way repeated measure analysis of variance (ANOVA) was used to analyze within subject factors for curve (two levels: straight v. curve interval) and distance (4 levels) for the variables of: (1) time, (2) $\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$, and (3) $TA_{MEAN\text{-}ave}$, $TA_{PEAK\text{-}ave}$, $LG_{MEAN\text{-}ave}$, $LG_{PEAK\text{-}ave}$ across each 100-m interval of the 800-m run. Pearson product-moment correlation coefficients were assessed between $\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$ and $TA_{MEAN\text{-}ave}$, $TA_{PEAK\text{-}ave}$, $LG_{MEAN\text{-}ave}$, and $LG_{PEAK\text{-}ave}$. Additionally, Pearson-product moment correlations were used to evaluate if better performance (final time) was influenced by changes in FSP (difference between FSP of last and first straight). A paired samples t-test was used to analyze lactate from before and after the 800-meter run.

CHAPTER 4: RESULTS

PERFORMANCE

The mean final time of all subjects was 163.76 ± 24.11 seconds. A significant interaction effect was seen for distance*curve (F [3, 60] = 15.188, $p < 0.001$). Post-hoc analysis showed on the curves, curve 1 (first 100-m of the 800-m) was significantly faster than the subsequent three curves ($p < 0.001$), curves 2 and 3 were significantly faster than curve 4 ($p < 0.001$). On the straights, straight 1 (second 100-m of the 800-m) was significantly faster than 2, 3, and 4 ($p<0.001$). When comparing straights and curves at each interval (curve 1 to straight 1, curve 2 to straight 2, etc.), the only significant difference observed was between the 4th straight and curve, where the straight was significantly faster than the curve ($p<0.001$) (Figure 6).

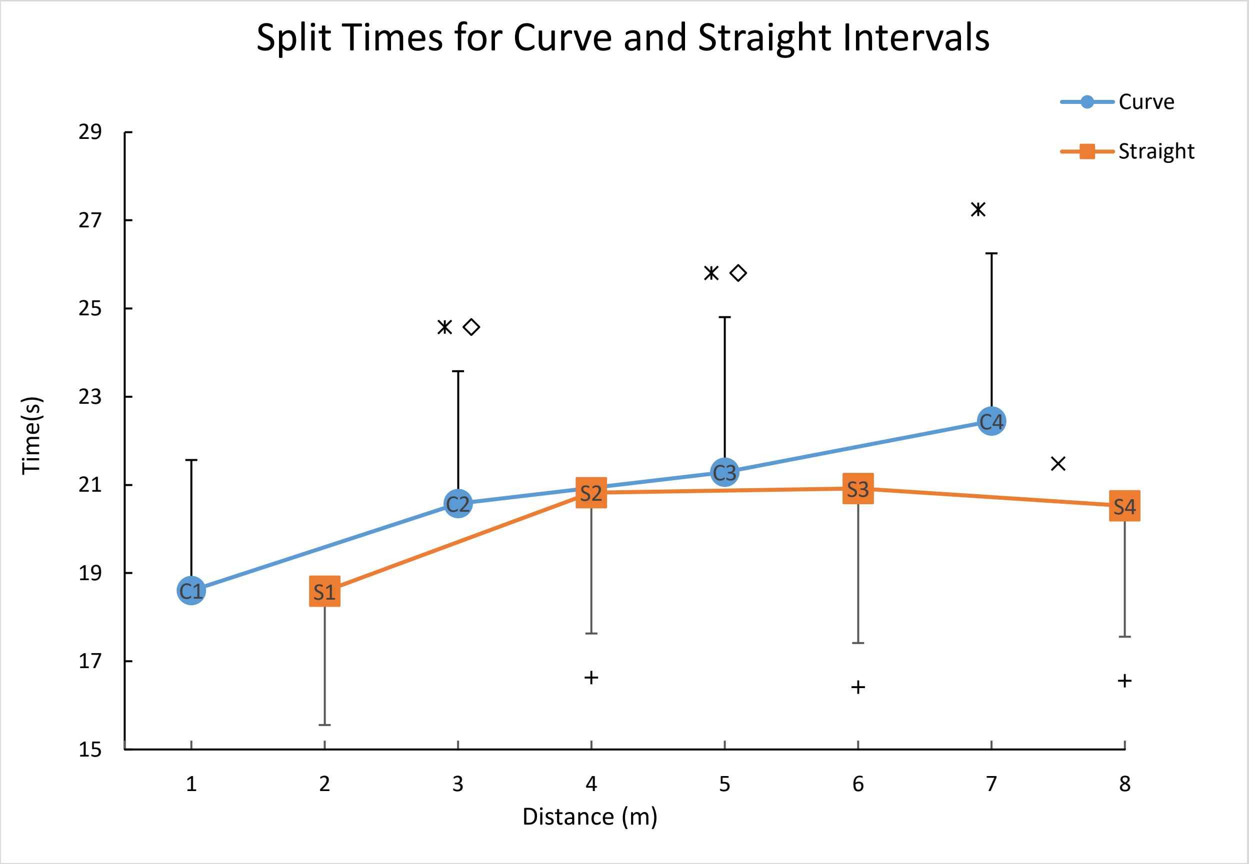

Figure 6. Split time for curves and straight intervals. C1 signifies "Curve 1," S1 signifies "Straight 1." *- significantly different from C1; ◊ - significantly different from C4; + - significantly different from S1; × - significant difference between C4 and S4.

ANGULAR VELOCITY OF THE FOOT

Considering the effects of distance and curve on $\omega_{FS\text{-}ave}$, there were no significant effects seen for distance*curve interactions (F [3, 60] = 0.441, p=0.725) or distance (F [3, 60] = 0.531, p= 0.662). A significant effect was seen for curve (F [1, 20] = 21.707, p<0.001). Post-hoc analysis revealed a significant difference between curves and straights (p<0.001), where the straight intervals had significantly higher $\omega_{FS\text{-}ave}$, meaning less plantarflexion, compared to the curve intervals (Figure 7).

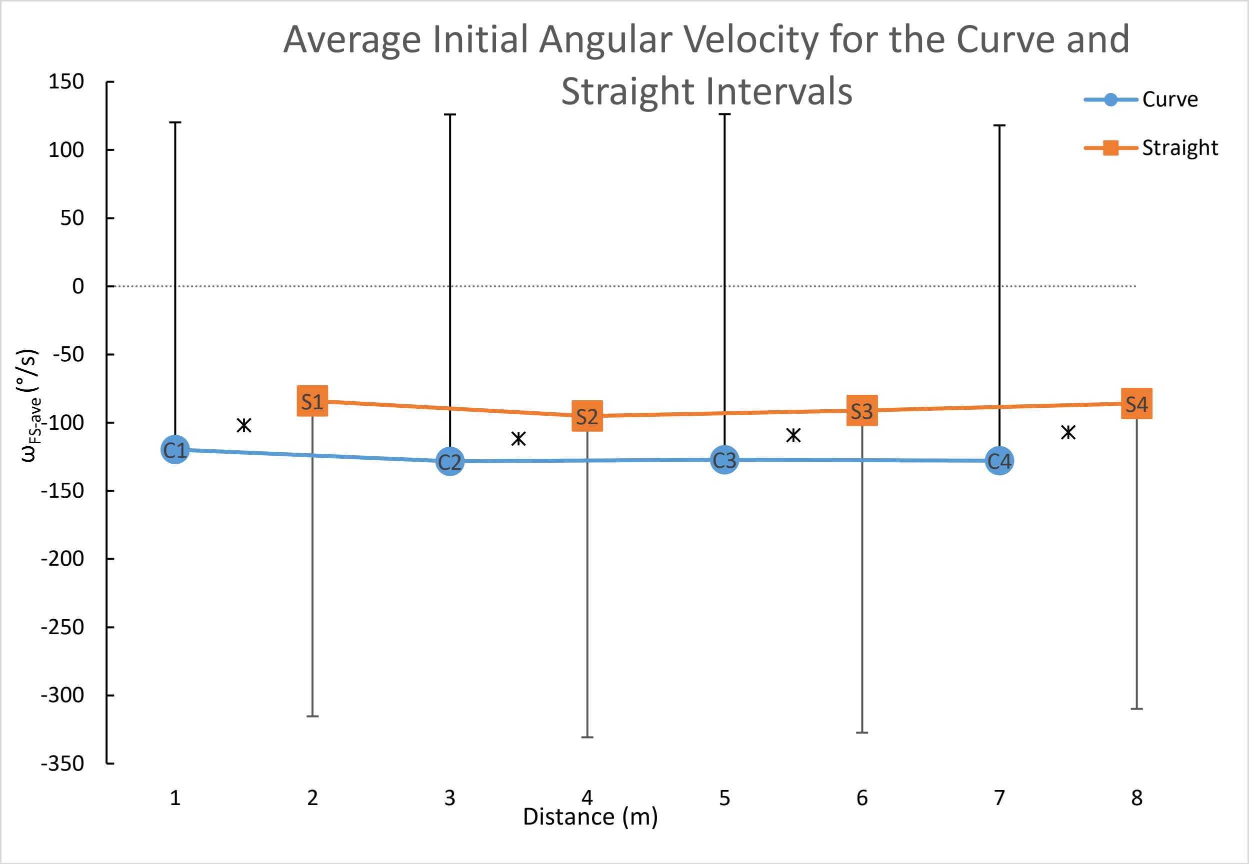

Figure 7. $\omega_{FS\text{-}ave}$ for the straight and curve intervals. C1 signifies "Curve 1," S1 signifies "Straight 1." * - significant difference between curves and straights at the .05 alpha level.

CHANGE IN FOOT ANGLE

Similar to $\omega_{FS\text{-}ave}$, $\Delta\theta_{ave}$ an of distance*curve (F [3, 60] = 1.291, p=0.286) or distance (F [3, 60]= 2.219, p=0.095) was not seen. However, a significant effect was shown for the effect of curve (F [1, 20] = 18.445, p<0.001) with significant differences between curves and straights (p<0.001) (Figure 8). The $\Delta\theta_{ave}$ values during the straight intervals were significantly greater than for the curves, again indicating less FF plantarflexion.

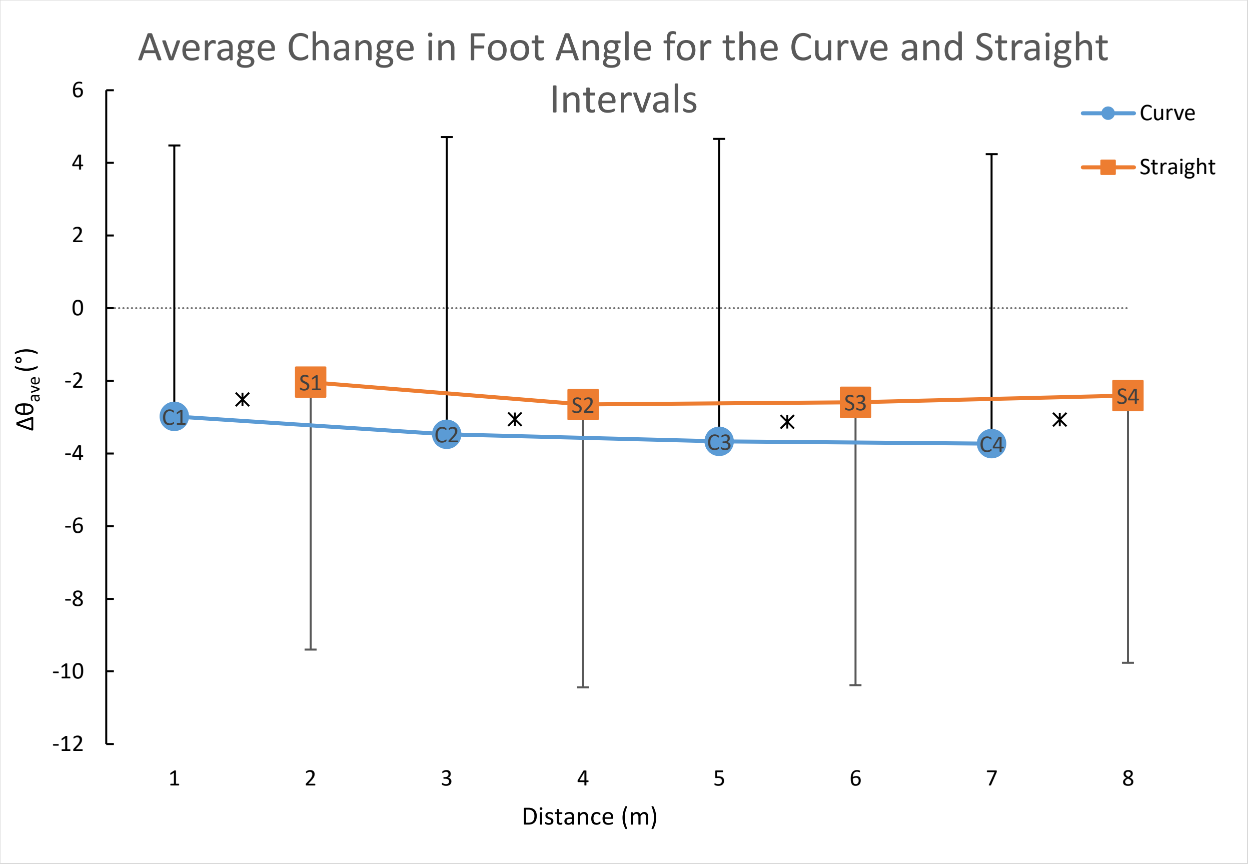

Figure 8. Mean change in foot angle for curve and straight intervals. C1 signifies "Curve 1," S1 signifies "Straight 1." * - significant difference between curves and straights at the .05 alpha level.

EMG

One subject was excluded for the analysis of EMG because of a sensor error during the trial, leaving 20 subjects for this analysis. For $TA_{MEAN-ave}$, no significant effect was observed for curve (F [1, 19] = 0.036, p=0.852) or distance*curve interaction (F [3, 57] = 0.911, p=0.442). A significant effect was seen for distance (F [3, 57] = 3.118, p=0.033). Post-hoc analysis revealed interval 1 (curve 1 and straight 1) was significantly greater than intervals 2 (curve 2 and straight 2) (p=0.022), 3 (curve 3 and straight 3) (p=0.036), and 4 (p=0.017) with no other significant differences observed (Table 2).

$TA_{PEAK\text{-}ave}$ showed no significant differences for the effect distance*curve interaction (F [3, 57] = 1.213, p=0.313), curve (F [1, 19] = 0.351, p=0.560), or distance (F [3, 57] = 1.756, p=0.166) (Table 2).

The $LG_{MEAN\text{-}ave}$ across distance and curve showed similar results to that of the TA. A significant effect was seen for distance (F [3, 57] = 2.949, p=0.040), but not for curve (F [1, 19] = 2.579, p=0.125) or distance*curve interaction (F [3, 57] = 2.333, p=0.084). Post-hoc analysis revealed interval 2 was significantly greater than interval 3 (p=0.046), but no other significant differences were observed (Table 2).

$LG_{PEAK\text{-}ave}$ showed a significant difference for the effect of distance (F [3, 57] = 3.139, p=0.032), but not curve (F [1, 19] = 2.166, p=0.157) or distance*curve interaction (F [3, 57] = 2.680, p=0.055). However, post-hoc analysis for the effect of distance did not reveal any significant differences (Table 2).

		Tibialis Anterior		**Lateral Gastrocnemius**	
		$TA_{MEAN\text{-}ave}$	**$TA_{PEAK\text{-}ave}$**	**$LG_{MEAN\text{-}ave}$**	**$LG_{PEAK\text{-}ave}$**
Distance Interval 1	Curve 1	0.94 ± 1.88	4.45 ± 12.52	0.92 ± 1.89	3.98 ± 8.13
	Straight 1	0.929 ± 2.01	5.32 ± 16.23	0.76 ± 1.45	3.37 ± 6.58
Distance Interval 2	Curve 2	0.774 ± 1.65 *	4.46 ± 13.13	0.577 ± 0.875	2.741 ± 4.76
	Straight 2	0.697 ± 1.56*	4.08 ± 12.57	0.502 ± 0.75	1.84 ± 2.47
Distance Interval 3	Curve 3	0.76 ± 1.71*	4.59 ± 14.62	0.475 ± 0.82^	1.88 ± 3.26
	Straight 3	0.773 ± 1.75*	4.203 ± 13.01	0.453 ± 0.79^	1.87 ± 3.27
Distance Interval 4	Curve 4	0.719 ± 1.67 *	4.17 ± 13.61	0.438 ± 0.71	1.82 ± 3.34
	Straight 4	0.823 ± 2.32*	4.54 ± 15.55	0.44 ± 0.6	1.95 ± 3.03

Table 2. Muscle activity (mV) for the Tibialis Anterior and Lateral Gastrocnemius during each distance interval on curves and straights. * - significantly different from Distance Interval 1; ^ - significantly different from Distance Interval 2.

EMG AND FSP

Pearson-product moment correlations were performed on overall $TA_{MEAN\text{-}ave}$, $TA_{PEAK\text{-}ave}$, $LG_{MEAN\text{-}ave}$, and $LG_{PEAK\text{-}ave}$ with $\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$. Significant negative correlations were observed between both $\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$ with both $LG_{MEAN\text{-}ave}$, and $LG_{PEAK\text{-}ave}$ across all distance intervals. More LG activation correlated with a more plantarflexed foot direction. Table 3 displays the correlation coefficients observed between all measures. No significant correlations were observed with the TA for either foot strike measure.

Correlation Coefficients of Foot Strike and EMG Measures

	$TA_{MEAN\text{-}ave}$	$TA_{PEAK\text{-}ave}$	$LG_{MEAN\text{-}ave}$	$LG_{PEAK\text{-}ave}$
$\omega_{FS\text{-}ave}$	-0.107	-0.068	-0.530**	-0.540**
$\Delta\theta_{ave}$	-0.099	-0.062	-0.537**	-0.544**

Table 3. Correlation coefficients of foot strike measures ($\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$) and EMG Measures ($TA_{MEAN\text{-}ave}$, $TA_{PEAK\text{-}ave}$, $LG_{MEAN\text{-}ave}$, and $LG_{PEAK\text{-}ave}$). ** - significant difference at the .001 alpha level.

FOOT STRIKE AND FINAL TIME

Change in $\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$ over the course of the run were evaluated by subtracting the $\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$ during the final straight interval from the first straight interval. These values were correlated with final time to evaluate if a better performance was reflected in changes in FSP. No correlations were found between the variables evaluated ($\omega_{FS\text{-}ave}$: r= -0.034, p=0.884; $\Delta\theta_{ave}$: r=0.004, p=0.986).

LACTATE

A paired samples t-test for lactate measures revealed a significant difference between pre- and post-800 lactate levels (t (11) =-7.046, p<0.001). Due to difficulties with lactate sampling, reliable lactate samples were only available for 12 of the 21 subjects. Table 4 displays pre- and post-lactate values for the 12 samples.

Pre-Lactate	Post-Lactate
0.7	9.1
5.3	9.1
1.3	10.5
3.4	9.4
2.4	10
1.9	10.1
2.6	7.4
1.5	17.5
2	7.4
5.4	8.4
1.9	7.1
1.4	13.1

Table 4. Pre- and Post-lactate values for 12 subjects.

CHAPTER 5: DISCUSSION

The main findings of this study looking at FSP during a maximal 800-m run and their relationship with muscle activity revealed FSP did not change throughout an 800-m run, with runners remaining in a more FF strike pattern. In addition, there were significant differences seen in FSP between curves and straights, where a more FF strike pattern was used on the curve intervals compared to the straights. Finally, velocity for the first curve and straight were significantly higher than for all other intervals throughout the 800-m run.

PERFORMANCE

Firstly, when considering the split times for our subjects, we saw a significant decrease in speed throughout the 800-meter run from interval one to eight, except for the final interval, where time decreased. This most likely occurred because the subjects had a “kick” during the last 100-meters of the run. When looking at the effect of distance*curve on split time, a significant interaction effect was observed. The first curve was run significantly faster than the subsequent three curves. Additionally, the first straight interval was run significantly faster than the following three straight intervals. Similarly, Hanon and Thomas (2011) showed the highest velocities during an 800-meter run occurred during the first 200-meters of the run. We saw a significant difference between the final curve and straight interval, where the final straight was faster than the final curve. This was most likely due to the “kick” during the final 100-meters of the run. However, Hanon and Thomas (2011) did not observe a decrease in time during the last 100-meters of an 800-meter run and stated there is typically a slowing of velocity during the last 100-meters. This difference between the present study and Hanon and Thomas’ (2011) results for velocity may be attributed to the differences in protocol. Hanon and Thomas (2011) used data from an actual race, whereas this study used a simulated race, and those runners were all racing to achieve a personal best time.

FOOT STRIKE PATTERN

We hypothesized there would be a change in FSP over the course of the 800-meter run evidenced by a shift from a more FF strike at the beginning of the run to a more RF strike pattern by the end of the run. The main finding of this study was FSP did not change significantly over the course of the 800-meter run. The ω_{FS} results throughout the race indicate the rotation direction of the foot. More negative values for ω_{FS} and $\Delta\theta$ indicate landing with the foot in a more plantarflexed position, and more positive values indicate landing with the foot in a more dorsiflexed position. Since this value stays negative, it implies that the foot did not change its directional rotation and therefore maintained a FF strike throughout the race. Similar conclusions can be made by considering the $\Delta\theta$ data. Our method indicating a change in angle is comparable to the methods used by Altman and Davis (2012) to determine FSP. Their method using a motion analysis system and visual markers found that an angle change from foot strike to stationary standing of less than -1.6 degrees signifies a FF strike pattern (Altman & Davis, 2012). Similarly, a difference between angle at foot strike and angle at foot stationary using accelerometer data was used in this study. Our average results throughout the race are below -1.6 degrees, signifying a FF strike pattern throughout the race.

When looking at the $\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$ of the foot, we saw significant differences for the effect of curve, where the curve intervals were significantly different from the straight intervals, and more FF strike pattern was evident on the curves compared to the straights. We believe this is the first study to show differences in foot strike between curve and straight running in an 800-meter run. There have been studies that have looked at differences in foot position and velocity during shorter running trials. It has been shown that running on a curved path is significantly slower than running on a straight path (Jain, 1980). Churchill, Salo, and Trewartha (2011) observed subjects running 60-meter maximal effort runs on an outdoor track. The authors found race velocity and absolute speed were significantly reduced on the bend compared the straight. When looking at the right foot during the run (outside foot), decreased velocity was caused by a reduction in step length in that study. Additionally, right leg flight time decreased on the bend, indicating the athletes were not able to generate the same vertical and propulsive forces as on the straights. This was most likely due to the additional requirement of centripetal force generation on the bend (Churchill et al., 2011). Hamill, Murphy, and Sussman (1987) also observed runners on an outdoor track running at a pace around 4:15 minutes per mile. Hamill et al (1987) explained as a runner moves around the bend of a track, they must apply a shear force away from the center of the curve, resulting in centripetal force generation. This centripetal force produces a torque rotating the runner’s body away from the vertical and center of the track curve and to counteract this torque, modifications in the lower extremity and body position are necessary (Hamill et al., 1987). Additionally, the authors found the right foot was always in an exaggerated supinated position of at least five degrees more on the curve compared to the straight (Hamill et al., 1987). Supination is characterized by FF adduction, inversion of the foot, and ankle plantarflexion (Dugan & Bhat, 2005). The FF strike pattern is characterized by greater plantarflexion, inversion of the foot, and supination at foot contact (McClay & Manal, 1995; Williams III et al., 2000). Therefore, it can be assumed a more FF strike is used when running on curves compared to straights.

Our observations were limited to analyzing only the right foot during this 800-m run, however, there is evidence to suggest that the left foot is also affected by running on curves. Chang and Kram (2007) observed the peak resultant ground reaction forces decreased on the curve for both feet compared to running on the straight, however this was even more exaggerated for the inside left foot. Churchill and colleagues (2011) showed there was a reduction in velocity of the left foot on the curve due to both step length and step frequency. The authors proposed step length decreased due to an increase in ground contact time, which may have been to allow for the need for increased centripetal force generation. Step length was decreased due to a smaller proportion of total step spent in flight (Churchill et al., 2011). In addition, these effects may be even more exaggerated on tighter curves or those with smaller radii, such as an indoor track curve (Chang & Kram, 2007; Hamill et al., 1987).

Overall, we did not see a change in FSP over the course of the run. Previous studies looking at changes in FSP throughout a run have been done in much longer distances than an 800-meter run. For example, in a marathon, it has been observed that the percentage of FF runners declines as the race progresses, with many of those runners switching to a more posterior landing (Larson et al., 2011). Jewell et al (2017) observed FSP during a 15-20 minute fatiguing run on a treadmill and found a transition towards a more MF strike pattern in runners who began with a FF strike. In race scenarios, there have been few studies evaluating FSP throughout the run and have used other variables to make inference about the changes in FSP. For example, Elliot and Ackland (1981) used high-speed video cameras during the 10,000-m final at the Australian Track and Field Championships. The authors found throughout a 10,000-meter race, there tends to be a decrease in the relative backwards velocity of the ankle at foot strike, creating a greater likelihood of a RF strike in these elite runners (Elliot & Ackland, 1981). In a study of 800- and 1500-meter runners, Hayes and Caplan (2012) observed elite 800- and 1500-m runners at an elite level race using a high-speed video camera. The authors found an increase in ground contact time throughout the race. Although changes in FSP over the course of the race were not monitored, the increase in ground contact time could be indicative of a shift to striking more posteriorly on the foot (Hayes & Caplan, 2012). Although these studies can be used to make conjectures about changes in FSP, there is not concrete evidence to support that a change in FSP does occur during these shorter distance races. It is possible that the 800-meter is not a long enough race to elicit the amount of fatigue necessary to cause a shift in FSP. There is also the potential that our subjects did not perform at their maximal capacity during the study and therefore did not produce the degree of fatigue needed to induce changes in FSP. When looking at velocities during an 800-meter run, Hanon and Thomas (2011). observed a decrease in velocity throughout the 800-meter race, with no increase in velocity during the last 100-meters. Our results showed an increase in velocity during the last 100-meters of the run, meaning the subjects may have not given forth a maximal effort.

These observations of foot strike during a race have been made using high-speed video cameras and either did not have the technology available or were not able to directly measure FSP. FSP has been able to be measured directly in laboratory settings, however these protocols occur on a treadmill. It has been shown treadmill running and overground running are not the same (Nigg et al., 1995). Nigg and colleagues (1995) looked at kinematic differences between overground and treadmill running and found their subjects landed with their foot in a flatter position on the treadmill than in overground running. Frishberg (1983) explained that the moving treadmill belt reduces the energy requirements of the runner by bringing the supporting leg back under the body during the support phase of running in their study of sprinting on the treadmill versus overground. Similarly, Elliot and Blanksby (1976) found at faster velocities of 4.82-6.2 m/s, significant differences were present between overground and treadmill running. The authors found decreases in stride length, increases in stride rate, and the period of non-support was significantly less when running on a treadmill compared to overground running (Elliott & Blanksby, 1976). With this evidence, there are apparent differences in overground and treadmill running, making the need to measure kinematic variables during overground running extremely important. Recent advancements in technology enabled the present study to directly evaluate FSP during overground running with the use of a functional IMU.

MUSCLE ACTIVITY

When looking at muscle activity, the $\mathrm{TA}_{\mathrm{MEAN\text{-}ave}}$ activity appeared to decrease throughout the run. The first interval showed significantly more muscle activity than the remaining intervals of the run. A similar pattern was observed for the $\mathrm{LG}_{\mathrm{MEAN\text{-}ave}}$, however the significant difference was observed between intervals 2 and 3, where interval 2 was greater than 3. There were few other significant differences found, however, the general trend of all measures was a decrease throughout the run. These results were unexpected, as we believed there would be an increase in EMG throughout the run due to the subjects becoming fatigued and requiring the recruitment of additional motor units in order to maintain velocity. Nummela et al (1994) looked at EMG throughout a 400-meter sprint and saw an increase in rectus femoris EMG. The authors believed this was due to the recruitment of additional motor units (Nummela et al., 1994). When looking at other studies which have used fatiguing protocols and observed EMG before and after running, increases in gastrocnemius EMG were also seen (Nicol et al., 1991). However, a reduction in EMG during a run is not unheard of. In a 5000-meter time trial, Nummela et al (2006) observed a decrease in gastrocnemius, rectus femoris, biceps femoris, vastus lateralis, and vastus medialis EMG activity. The authors also saw a reduction in velocity throughout the run and believed the decrease in muscle activity could be attributed to the subjects slowing down throughout the run (Nummela et al., 2006). A reduction in velocity throughout the run was also seen in this study, and therefore the decrease in muscle activity observed could be attributed to this reduction in running velocity.

There is also the question of sensor validity for the EMG measurements. Although these sensors have been used in a previous study to look at muscle activity (McGinnis et al., 2018), the validity of these sensors during intense physical activity is unknown. Our data showed random high amplitudes for many subjects, of which the reason for is unknown. In addition, we did not normalize our EMG data to maximal voluntary contractions for each subject because we were only performing within-subject analyses instead of between-subject analyses. This could partially be a cause for the strange nature of the EMG data. Finally, the EMG data was amplified through the company software, giving extremely high values, and could also be a cause for odd data.

MUSCLE ACTIVITY AND FOOT STRIKE PATTERN

Finally, we investigated the relationship between muscle activity and FSP. When doing this analysis, we did not correlate lactate with FSP due to only having reliable lactate data for half of the subjects. Significant negative correlations were observed between both $\omega_{FS\text{-}ave}$ and $\Delta\theta_{ave}$ with $LG_{PEAK\text{-}ave}$ and $LG_{MEAN\text{-}ave}$. We observed a more FF position of the foot was related to increased LG muscle activity. This result is in line with other research. It has been shown that in FF strikers, where the foot lands in a more plantarflexed position (Landreneau et al., 2014; Williams & Cavanagh, 1987), the medial and lateral gastrocnemii muscles are activated earlier and longer (Ahn et al., 2014). Earlier activation of the gastrocnemii muscles allows for plantarflexion of the ankle joint to prepare for landing and increases the capacity of the passive structures to store elastic energy at foot contact (Adrigo et al., 1995; Ahn et al., 2014; Perl et al., 2012). Pre-activation of the gastrocnemii muscles increases storage capacity of the elastic tissues in the lower leg by stretching the Achilles tendon before landing (Ahn et al., 2014; Roberts, 2002). When the tendon has tension before landing, the force of landing stretches the tendon more, allowing for greater storage of elastic energy (Ahn et al., 2014).

LIMITATIONS

Unfortunately, limitations were difficult to avoid during this study. Due to the fact that this study was performed outside, the effect weather may have had on the subjects' running ability must be taken into account. The temperatures during the testing period of this study and track conditions were not always ideal. Additionally, it is hard to determine if the subjects were able to run a true maximal 800-meter run. In a race environment, there are other competitors, a stressful environment, and fans that all lead to better performances. It was impossible to simulate a true race environment in this way. We opted to have the subjects run in their regular training shoes rather than a racing flat or spike because the subjects who were not current collegiate athletes most likely would not have had this type of shoe. Had our collegiate population of subjects been allowed to wear their typical racing shoes, it is possible our foot strike data may have looked differently. Finally, we are concerned with the validity of the sensor measurements for EMG.

CHAPTER 6: CONCLUSION

The main findings of this study were FSP did not appear to change over the course of this outdoor 800-m race, with subjects remaining in a more FF strike pattern. This study was the first to show there were significant differences in FSP seen between running on the curves and straights during a maximal 800-meter run. Running on the curves produced a more FF strike pattern when compared to running on the straights. With curve running, the outside (right) foot must land in a more supinated and inverted position in order to produce the medio-lateral forces necessary to move through the curve in the most efficient manner (Hamill et al., 1987). With this knowledge, it is possible that more attention needs to be given to training curve running technique. Future research should look into the asymmetries between right and left FSP on curves and straights during race, or simulated race, scenarios.

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Vita

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