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THE EFFECTS OF UPHILL, DOWNHILL, AND LATERAL ROLL TREADMILL RUNNING: AN EMG, KINEMATIC, AND METABOLIC ANALYSIS

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ABSTRACT

Previous research has confirmed that training on a sagittal plane tilt can elicit performance benefits that translate into level running, so it is interesting to see whether this holds true for a training program that incorporates running on a combination of left and right frontal plane roll. It would be extremely useful to the world of sports to determine whether this type of training would increase the runner's ability to respond to the natural terrain effectively, thereby avoiding injury and performance hindrance. Hence, the purpose of this experiment is to determine whether it is possible to train the human body to be efficient in responses to running on a frontal plane roll. I will analyze modifications in biomechanical and metabolic parameters in response to five different slope conditions (level, 3° up, 3° down, 3° left, and 3° right). I am particularly concerned with changes in response to frontal plane roll (left & right), but I will collect data for level, up, and down as a means of comparison.

I recruited 15 healthy college students, all of whom were trained, distance runners, to complete a unique protocol that determined changes in muscular, metabolic, and kinematic parameters with respect to the direction of tilt and roll during treadmill running. The protocol required that each participant run on a treadmill (3m/s), for seven minutes at each slope condition. I measured changes in EMG for 8 separate muscles (TA, LG, SL, BF, RF, VL, ADL, & TFL). I also analyzed temporal-spatial variables and oxygen consumption ($ml \cdot kg^{-1} \cdot min^{-1}$) for each of the five conditions.

Because there is currently no research concerning treadmill running on surfaces sloped in the frontal plane, I based my hypotheses about roll running upon previous literature regarding uphill and downhill running. I hypothesized that there would be

significant changes in muscle activity for certain running muscles relative to slope condition and gait phase. More specifically, I expected that most of these changes in EMG activity would occur in the joint stabilizers of the hip, knee, and ankle. Additionally, I hypothesized greater *total* muscle activity compared to level and downhill, but less activity compared to uphill running. Furthermore, because changes in muscle activity are positively correlated with changes in metabolic demands, I hypothesized an increase in metabolic activity compared to level and downhill, but a decrease compared to the uphill condition. In regards to kinematics, I hypothesized significant changes in gait patterns, particularly temporal-spatial parameters, in order to adjust to roll running. Specifically, I anticipated increased swing time for the lower leg during left and right roll, as well as a greater step width to enhance the base of support.

Trends in EMG, metabolic, and kinematic activity for sagittal plane tilt were consistent with previous literature. Conversely, there is not enough evidence to support my hypotheses about specific biomechanical and metabolic changes relative to frontal plane roll. In short, these results illustrate that running on a frontal plane roll elicits changes in gait patterns; however, these exact changes are not well defined. In order to attain more significant conclusions, it may be beneficial to manipulate grade, speed, and the duration of data collection for future studies

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CHAPTER 1: INTRODUCTION

Practical Significance

Coaches, trainers, and performance athletes are heavily reliant on the notion that incorporating uphill and downhill-sloped running into a training regimen will elicit performance improvements on level ground. It is highly recommended, regardless of the event distance, that runners “hill train” for a meet or race (Hirschmuller et al., 2007). This method is frequently used by sprinters and distance runners as a means for creating gains in aerobic capacity, muscle strength, and mental toughness that will transfer to race day (Heikki et al. 1978). In fact, it has been determined that an eight-week training program that incorporates a combination of uphill and downhill running on a 3° slope will enhance level ground performance by increasing maximum running speed by 4.7% and step rate by 4.8% (Paradisis & Cooke, 2001). Several studies have considered the effects of running uphill and downhill (Paradisis et al., 2001; Iverson et al., 1992; Mueller et al., 2010); however, there is no current research that reflects the effects of running on a frontal plane slope.

Would a training program that incorporates running on a combination of left and right frontal plane roll be useful for a sprint or distance runner? This could be especially useful for a cross country runner, seeing as they are constantly running on uneven terrain, rather than a track or a street path. Perhaps this type of training would increase the runner’s ability to respond to the natural terrain effectively. By researching this question, I may determine whether it is possible to train our bodies for muscular, metabolic, and kinematic responses to a lateral roll in a way that enhances performance benefits. After all, distance running is highly dependent on the ability to successfully maintain a consistent pattern of muscle movement and energy expenditure despite the outside circumstances (Iverson & McMahon, 1992). Because several distance runners often face environmental obstacles such as hilly or rocky terrain, it is important to determine how these variables directly affect running performance. Therefore, the primary objectives for this study are to determine how muscular, metabolic, and kinematic parameters change with respect to the direction of tilt (sagittal plane) or roll (frontal plane) during treadmill running.

Electromyography

The level of muscle activity during locomotion is dependent upon the number of muscle fibers activated, and the extent to which these motor units are recruited as a function of their total capacity. The direction and gradient of the surface, among several factors, will alter the activity of the muscles involved in running. Some muscles will be recruited more than others, while others may cease activity entirely. These changes will be experimentally determined in eight different muscles: tibialis anterior, lateral gastrocnemius, soleus, biceps femoris, rectus femoris, vastus lateralis, adductor longus, and tensor fascia lata. I will use surface electrodes to measure the activity of each muscle on a level surface, at a 3° upward tilt, a 3° downward tilt, a 3° left roll, and a 3° right roll. I will break the gait cycle into seven different phases: initial, middle, late, and terminal stance, as well as initial, middle, and terminal swing. I will analyze each phase to determine changes in activity for the eight muscles relative to the direction of the slope.

I am mostly concerned with the 3° leftward and rightward roll since there is no current research regarding frontal plane sloped running. I will also compare my results for level, uphill, and downhill running to other findings from current literature.

Level Running

The *tibialis anterior (TA)* is active throughout most of the gait cycle. The primary burst of maximum activity occurs at heel-strike, where it contracts eccentrically as the foot is lowered to the ground (Elliot & Blanksby, 1979). During mid-support, when the foot is flat, there is a secondary burst of activity in which the TA acts concentrically to bring the shank forward. During late support, the TA exhibits electrical silence (Mann & Hagy, 1980a; 1980b), but constant activity is resumed during the swing phase, where it works to control ankle extension and initiate ankle flexion.

The *lateral gastrocnemius (LG)* acts eccentrically to help decelerate the shank during the late swing phase (Schwab et al., 1983). It is interesting to note that this eccentric contraction occurs coincident with the concentric contraction of the TA to help stabilize the foot for heel-strike. It is eccentrically active from late swing until about 50-80% of stance phase, depending on running speed (Elliot & Blanksby, 1979). At toe-off, the LG contracts concentrically to assist with ankle extension. There has been some controversy regarding which of these is the primary, maximal burst of activity; however it is mostly reported that maximum activity occurs with the concentric contraction observed at toe-off (Elliot & Blanksby, 1979). The *soleus (SL)* appears to have the same function and pattern of electrical activity as the LG.

The *biceps femoris (BF)* is part of a group of muscles known as the “hamstrings”. Because the long head of the BF has an origin on the posterior ischial tuberosity, it acts to extend the hip in addition to flexing the knee. There is no activity observed during early to mid-swing because the knee is passively flexed. The BF then acts eccentrically to decelerate hip flexion and control knee extension through the last 25-40% of the swing phase (Schwab et al., 1983). Once forward swing is complete, just prior to heel-strike, the BF acts concentrically to extend the hip and flex the knee in preparation for the cushioning phase of heel-strike. This activity increases throughout stance, until toe-off, where it achieves a maximum burst of activity (Elliot & Blanksby, 1979).

The *rectus femoris (RF)* is the only muscle of the quadriceps muscle group that crosses the hip, which gives interesting insight into the muscle activity associated with hip flexion. In addition to hip flexion, the RF acts with other quadriceps muscles to extend and stabilize the knee during locomotion. The RF exhibits two phasic patterns of activity. The primary burst occurs during late swing, and lasts through the first half of the stance phase (most authors). An additional secondary burst of activity can be seen during early swing, and is associated with the hip-flexor function of the RF (Nilsson et al., 1985).

The *vastus lateralis (VL)* is another member of the quadriceps muscle group; however this muscle does not cross the hip joint, so it acts only to control movement about the knee (Mann & Hagy, 1980a; 1980b). Similar to the RF, a primary phasic burst of activity is associated with knee extension during terminal swing. There is also some activity associated with stabilizing the patella during the contact phase, and in some cases, a secondary phasic pattern of activation is observed during mid-swing (MacIntyre et al., 1987). It is interesting to note that quadriceps (RF and VL) lengthen, while active, due to partial knee flexion at the time of heel strike. This indicates a “co-activation” pattern between the hamstrings and quadriceps for stability and cushioning of impact at footstrike.

It is widely accepted that the *adductor longus (ADL)* shows continuous activity throughout the entire gait cycle, despite running speed (Mann & Hagy, 1980a). With an origin on the superior aspect of the pubis, and an insertion on the middle 1/3 of the medial femur, the ADL is particularly important for stabilizing the pelvis during support, and stabilizing the thigh during the swing phase (Nilsson et al., 1985).

The *tensor fascia lata (TFL)* has fibers oriented in the anteromedial direction (AM fibers) and the posterolateral direction (PL fibers), indicating two distinct functions (Mann & Hagy, 1980a). The AM fibers are primarily hip flexors, and the PL fibers are hip internal rotators and abductors. The orientations of these fibers produce two phasic patterns of activity in the TFL. The primary burst is associated with activation of the PL fibers prior to, and immediately following footstrike. The second burst is observed only with high speeds, and is characterized by an activation of the AM fibers from toe-off into mid-swing.

Uphill Running

It has been consistently found that there is a greater total activation of the lower limb muscles during uphill running compared to that of level running (Mitsui et al., 2001; Lay et al., 2007; Slawinski et al., 2008). During high intensity uphill running, total volume of lower limb muscles recruited increases from 67% to 73% (Swanson & Caldwell, 2000). Although increased lower extremity muscle recruitment is a statistically significant finding across all studies regarding uphill running in the sagittal plane, it does not give a comparison *between* most muscles (Sloniger, 1997). Some of the significant changes worth noting were found in study comparing the muscle activity of elite sprint runners on a level versus uphill (3.1° ± 0.4°) surface (Slawinski et al., 2008). A decrease in BF activity was observed during the contact phase. There was also a decreased activity of the VL observed during the flight phase. This may, however, be attributed to the decreased hip extension in conjunction with increased knee flexion occurring at footstrike with uphill running. Additionally, an increase in the activity of the RF during stance was found in a separate study of uphill running (Yokozawa et al., 2007). In a study analyzing the electromyographic effects of sloped surfaces on locomotion, (Lay et al., 2007) significant increases in the mean activity of stance phase bursts were observed during uphill *walking* for seven of the eight muscles (gluteus maximus, RF, vastus medialis, BF, semimembranosus, SL, medial gastrocnemius, and TA) studied. The increased mean activity accounts for both an increase in magnitude of the burst, and an increase in the duration of the burst. The only muscle that did not exhibit significant changes was the TA (Lay et al., 2007).

Downhill Running

There have been very few publications reporting findings for the changes in muscle activity with downhill running, all of which have shown inconsistent findings. There is, however, literature with fairly consistent findings for muscle activity changes during downhill *walking* (Lay et al., 2006). All literature report increased burst durations for both the medial gastrocnemius (MG) and the RF (Mitsui et al., 2001; Tokuhiro et al., 1985; Lay et al., 2007). Additionally, there is a prominent hamstring burst observed during midstance (Mitsui et al., 2001), and no change in burst duration for the TA (Tokuhiro et al., 1985). The magnitude of activity for the RF, vastus medialis (VM), and TA all showed significant increases, while the MG showed significant decreases. Furthermore, the burst durations for the RF, VM, MG, and the SL all increased significantly, (Lay et al., 2007). Therefore, in contrast to uphill walking, the previously mentioned study analyzing the electromyographic effects of sloped surfaces on locomotion, there were significant changes in the mean activity for only three of the eight muscles observed (Lay et al., 2007).

Hypothesis

I expect to see a significant change in muscular activity for muscles associated with motion and stabilization of the lower limbs with running on a lateral roll. I hypothesize that running on a lateral roll will increase the muscular activity of the TFL and the ADL, seeing as these muscles are predominantly associated with joint stabilization during locomotion.

In comparison to level running, I hypothesize greater activity in the left knee stabilizers during a right roll; particularly the RF and the VL. According to previous literature, the work associated with maintaining muscular stability accounts for about 6% of total muscular work (Swanson et al. 2000). I also expect to see a significant increase in left leg ADL activity because it is constantly working to resist the downward slope felt by the left (lower) leg, requiring a greater magnitude of concentric contraction throughout the gait cycle. Additionally, I expect to see increased TFL activity of the left leg due to eccentric contractions for providing stability.

During a leftward roll (right leg lower), I hypothesize decreased activity, compared to level, in the left knee stabilizers because the right leg is lower to the ground, and thus feeling more instability. I also expect to see an increase in the concentric contractions of the left TFL, however this may be a passive contraction attributed solely to compression of the TFL with the contact phase. In accordance with my hypothesis that the left ankle will pronate during leftward roll, I expect to see an eccentric contraction in the left ADL. Despite this being an eccentric contraction, I hypothesize that the left ADL will work actively to stabilize the left leg throughout the gait cycle.

Metabolic Activity

The energy generation pathway most associated with endurance training is known as aerobic metabolism (Saltin, 1973). This is a process of chemical reactions necessary to fuel the body with substantial energy needed for external work, and will be the metabolic pathway with which this study concerns. The oxygen we consume from the environment is carried through the bloodstream, and is directly involved with the creation of adenosine triphosphate (ATP), which is required for muscular contractions (Padykula et al., 1955).

The rate at which we inhale O_2 from the environment and exhale the CO_2 created by chemical reactions within the body is known as the rate of *pulmonary exchange.* This rate of gas exchange indicates metabolic changes associated with different levels of external work (Klein et al., 1997). This is commonly measured through a ventilator facemask and a spirometer, which measures the volume and concentration of inspired O_2 and expired CO_2. In this study, I will use this method to determine the changes in pulmonary exchange rates with respect to changes in the direction of sloped running.

Changes in metabolic costs are closely linked to changes in muscle activity of the muscles associated with running. These changes in muscle activity are frequently affected by changes in movement patterns, which can be elicited by manipulating variables such as speed, gradient, and direction of running (Williams, 1980).

By measuring metabolic rates, I will also be able to determine the running economy for individuals involved with this protocol. Running economy can be defined as the VO_2 for a given submaximal running velocity, and this can be linked to performance with studies focused on distance running (Williams & Cavanagh, 1987). Using this knowledge in addition to the metabolic data from this study, I will be able to determine whether or not there are aspects of running mechanics that allow one to ‘perfect’ the most efficient form of running. In other words, I will be able to determine whether there are certain parameters that can increase running economy in such a way that it will enhance performance.

These experiments can often be very difficult to control because there are many environmental factors (i.e. climate, terrain, gradient, and gravity) that can affect the work of locomotion. There is also extreme inter-individual variability, even with people of similar running abilities. There are numerous physiological factors (i.e. muscle fiber composition, training state, heart rate, gender, age, etc.), psychological factors (i.e. state of relaxation, ability to dissociate from pain), and biomechanical factors (i.e. stride length and frequency, degree of flexion and extension, range of movement about the joints) that impact running economy. For this experiment, I am mostly concerned with metabolic changes associated with a 3° leftward and rightward roll since there is no current research regarding metabolics during sloped running in the frontal plane. I will also compare the results for level, uphill, and downhill running to other findings from current literature.

Level Running

The cost of level walking and running has been extensively investigated in past literature. According to a study examining the energy cost of running on different slopes, the average metabolic cost for level running at 3.13 ± 2.2 m/s was 35.5 ± 2.7 $ml \cdot kg^{-1} \cdot min^{-1}$ (Minetti et al., 2001). Another study tested participants at 3.3 m/s on a level gradient, and found an average metabolic cost of 39.5 ± .30 $ml \cdot kg^{-1} \cdot min^{-1}$ (Klein et al., 1997). As previously stated, the inter-individual variability affecting these values makes it difficult to make conclusions about running economy. It is important to experiment with a fixed speed at different slopes so that there is a means of comparison for determining how running economy fluctuates.

Uphill Running

According to past literature, uphill surfaces induce an increased rate of oxygen consumption for running at a fixed speed, compared to that of level running. In fact, previous investigators stated that the cost of running on a positive gradient increases as a function of increasing slope up to 8.5° (Margaria et al., 1963). Consistent with these implications, the aforementioned study (Minetti et al., 2001) shows VO_2 values of 53.0± 8.6 ml•kg^{-1}•min^{-1} and 56.2± 4.4 ml•kg^{-1}•min^{-1} for grades of 5.3° and 11.5°, respectively. VO_2 also increased from 39.5± .3 ml•kg^{-1}•min^{-1} (level) to 53.3± .40 ml•kg^{-1}•min^{-1} (3.4° slope) for a fixed speed of 3.3 m/s (Klein, 1997). This increase in metabolic activity with increasing slope is a consistent finding across numerous studies.

Downhill Running

Few studies have incorporated metabolic changes with downhill running; however, markedly lower metabolic costs compared to level running have been consistently reported. Previous investigators have stated that the cost of running decreases linearly with negative slopes from -8.5° to -11.3°, but then begins to increase with more negative angles (Margaria et al., 1963). Thus, the optimal downhill slope for mechanical efficiency is between -5.7° and -11.3°. This is confirmed (Minetti et al., 2001) with VO_2 values of 23.3± 5.7 ml•kg^{-1}•min^{-1} and 18.9± 2.6 ml•kg^{-1}•min^{-1} for slopes of -5.7° and -11.3°, respectively. VO_2 then increased to 22.0± 3.1 ml•kg^{-1}•min^{-1} when the slope decreased further to -.30 (Minetti et al., 2001). Differences of 17.8 ml•kg^{-1} •min^{-1} were found for treadmill running at 3.83m/s (Williams & Cavanagh, 1987). There was also an upward drift of 2.8 ml•kg^{-1} •min^{-1} in VO_2 submax observed for prolonged downhill running, but not with level running (Dick & Cavanagh, 1987).

It has also been found that energy storage in running is consistent with a lower metabolic demand in muscle. This may, in fact, have implications associated with injury to the foot and leg muscles because of the large forces associated with downhill running (Margaria et al., 1963).

Hypothesis

Based on findings from past literature, and my hypothesis that there will be greater total muscle activity of the lower limbs during roll-running, I hypothesize that the metabolic work associated with lateral (frontal plane) roll will be greater than that of level and downhill running, but less than that of uphill running. It is important to note that this is dependent upon which way the treadmill is sloped, as well as how much the muscle activity is altered within each muscle.

Kinematics

The kinematics of running is used to describe how the lower body segments move in space to form a coordinated pattern of movement. I can use information about how the joints act together to determine changes in temporal-spatial parameters throughout the gait cycle with respect to slope changes.

By changing the direction or intensity of a gradient, the running velocity, or other external factors, I can determine how these patterns change. For the following study, I am particularly interested in gait changes associated with the direction of slope at a 3° grade. I am especially concerned with gait changes while running on a left and right frontal roll, because this has not been evaluated in previous literature.

For the kinematic portion of this experiment, I will determine which changes, if any, occur for joint angle patterns about the hip, knee, and ankle during treadmill running. Changes in these joint angle patterns, such as degree of flexion and extension, will present indications for gait changes relative to each slope. Differences in degree of flexion or extension will likely be congruent with changes in EMG activity observed for each muscle, thereby giving more credibility to my results.

I will also analyze various spatial-temporal variables to determine how the direction of slope affects the gait cycle in its entirety. The spatial-temporal variables I am mostly concerned with include swing time, stance time, step length, step frequency, ankle and toe step width (base of support), as well as changes in total stride time.

Level Running

Several studies have examined the kinematics of running on a level surface at a speed of 3.83m/s, and I will use the results about the hip, knee, and ankle joints to hypothesize potential gait changes with a frontal plane roll.

The hip begins to extend during the maximum support phase of stance, and continues through toe-off. It reaches maximum extension immediately after toe-off (Williams, 1980). Hip flexion begins during the swing phase, and reaches maximal flexion shortly before footstrike (Nilsson et al., 1985; Sinning, 1970).

At foot strike, the knee shows a slight flexion in preparation for the cushioning phase (Williams, 1980). This cushioning phase is a safety mechanism involving knee flexion immediately after footstrike, and is extremely important for injury prevention. This knee flexion continues through mid-stance, but then extends through late stance and toe-off. Toe-off marks the beginning of the swing phase, where maximum knee extension occurs. This maximum extension occurs in early swing, and is followed by a rapid flexion through mid-swing. Maximum knee flexion is attained just after mid-swing. Extension occurs in late swing to complete the gait cycle (Miller, 1978; Nilsson et al., 1985; Williams, 1980).

At footstrike, the ankle exhibits an approximated 90° angle of ankle flexion (Milliron & Cavanagh, 1990), followed by a very slight ankle extension immediately after footstrike. Maximum ankle flexion occurs during mid-stance, and it is important to note that this occurs simultaneously with maximal stance knee flexion. At toe-off, the ankle extends, reaching maximal extension shortly after toe-off. The majority of swing phase is characterized by a neutral, 90° angle of ankle flexion at the ankle joint (Sinning & Forsyth, 1970; Nilsson et al., 1985; Williams, 1980).

Uphill Running

Although most research studies the kinematics of level running, there has also been some recent literature interested in the kinematics of uphill running. One study evaluated trained distance runners during a 35 minute run with an average velocity of 213 ± 20.7 m/min. It was determined that there was no significant change in running mechanics when the runners were introduced to a 2.9° uphill for a 10 minutes period within the run (Klein et al., 1997).

In contrast to the findings by Klein et al., there is evidence that many changes do occur with uphill running. There is a significantly greater trunk lean with inline, as well as a decrease in stride length, and an increase in stride frequency to compensate for the shortened stride (Williams & Cavanagh, 1987). The changes in length and frequency may also contribute to the previously mentioned increase in metabolic cost.

It has also been observed that the lower limbs were more flexed throughout the stance phase with uphill running (Slawinski et al., 2008). There was greater flexion at the hip joint when the foot was directly below the hip, and there was also a greater total range of motion about this joint.

Additionally, swing flexion about the knee joint increased with increasing uphill slopes, as well as a greater flexion angle upon footstrike (Slawinski et al., 2008). Range of motion about the knee joint was said to decrease by 38% during the contact phase of stance when running on a 3.1° grade.

Past literature has also shown that flexion about the ankle joint increases prior to footstrike with uphill running. This increased ankle flexion also holds true during the stance phase of uphill running, followed by a decrease in ankle extension at toe-off (Milliron & Cavanagh, 1990). Interestingly, a 17% decrease in range of motion at the ankle joint has been observed during the contact phase (Slawinski et al., 2008), while experiments also show an increase in *total* range of motion about the ankle joint (Milliron & Cavanagh, 2008).

Downhill Running

Like that of uphill running, downhill running kinematics is not commonly observed. There is, however, substantial evidence according to recent literature, supporting the belief that mechanical changes do occur with downhill running. The trunk lean is significantly less than that of level running, but no significant changes in stride length (Dick & Cavanagh, 1987) or frequency (Tudus & Plyley, 1987) were reported.

It has been confirmed that some of the temporal parameters of gait are altered by a downhill slope. Specifically, an increased aerial time (swing phase) is observed with a -3.1° slope (Lay et al., 2006). This may be attributed to the fact that it takes the body longer to fall between steps as the treadmill is tipped downward.

With downhill surfaces, the flexion and extension angles are opposite of the findings for uphill running (Dick & Cavanagh, 1987). In addition to those findings, previous studies have also mentioned that the hip angle is less flexed during both swing and stance. The range of cushioning flexion about the knee increases and toe-off extension about the knee also increases with downhill surfaces (Milliron & Cavanagh, 1990).

Hypothesis

Based on the evidence presented in past literature, I suspect that the hip and ankle angles will change significantly with running on a lateral roll. I hypothesize a greater angle of supination in the left ankle with a rightward roll (left leg is lower), and vice versa for a leftward frontal plane roll. I hypothesize that the hip will tilt in the direction of the roll, so that the pelvis is parallel to the roll slope. I do not, however, expect to see significant angle changes in the knee joint.

I hypothesize that the trunk will maintain an upright angle, rather than tilting with respect to the roll. By maintaining a constant trunk angle despite changes in roll, the runners will maintain a stable and efficient pattern of movement.

For the purpose of this study, however, I am mainly concerned with the previously mentioned spatial-temporal variables. Consistent with findings from Lay et al. stating an increased aerial time for downhill running, I hypothesize an increase in aerial time (swing phase) for both legs with downhill running. I expect this change based on the theory (Lay et al., 2006) that the downward slope of the treadmill will cause the lower leg to remain in the air for a longer period of time compared to that of level running. Additionally, I hypothesize a greater stance time for the lower leg with lateral roll running. It is important to note that the right leg is lower (to the ground) during a left roll, and the left leg is lower during a right roll. I expect this change based on my hypothesis that the lower leg will be more important for stability purposes with lateral roll running.

I hypothesize a decreased total stride time for uphill running, which is congruent with observations made through previous research (Dick & Cavanagh, 1987), stating that an increased step frequency occurs with uphill running. Also in accordance with these findings, I expect to see a decreased step length to compensate for this predicted increase in step frequency with uphill running.

Additionally, I hypothesize an increased step length for downhill running. This corresponds to my previous hypothesis for an increased swing time during downhill running. This hypothesis assumes that more ground will be covered with each step due to the increased swing time.

Lastly, I do not expect to see any significant changes in step length or frequency with roll, and thus I do not hypothesize any changes in total stride time. I do, however, expect to see a greater stance time for lower leg compared to other leg with each roll condition. To compensate for this, I expect a subsequent decrease in swing time for the lower leg compared to the other for a lateral roll. Lastly, I hypothesize an increase in step width for frontal plane roll. I expect to see this as a means for increasing the base of support to maintain balance.

CHAPTER 2
MATERIALS AND METHODS

Participants

Fifteen healthy college students, 9 males and 6 females completed the protocol. All participants were experienced distance runners (conditioned to run 20+ miles per week at an 8:00 minute mile pace). All participants signed a written form of consent that followed guidelines of The Pennsylvania State Human Research Committee, as well as the Institutional Review Board (IRB).

Prior to set-up, I measured the participants' height and weight, as well as right and left leg length. I also measured hip width (measurement taken from one hip bone to the other) for kinematic purposes.

In order to measure kinematics, I placed 17 reflective markers on each participant: 1 cervical, 1 on each great digit, 1 on each fifth digit, 1 (large marker) on the right and left anterior iliac crest, an additional small marker on the right medial iliac crest, 1 (large and raised marker) on the sacral crest, 1 on the right shank, 1 on the left thigh, 1 on each lateral malleolus, and 1 on each lateral condyle. I taped all markers to skin with medical tape in order to avoid detachment during the protocol.

On the left leg, I located the muscle bellies of the eight muscles of interest: TA, LG, SL, RF, VL, BF, ADL, and TFL. It was important to locate the muscle bellies accurately so that I recorded the optimal EMG readings from each muscle.

In order to locate the muscle bellies properly, I used a tape measure and specific guidelines for finding the best placement. The ADL was palpated at the superior ramus of the pubis while the participant stood, conducting an isometric contraction. The electrode placement for the TFL was located 2-3 cm inferior to the iliac crest while standing. Electrode placement was diagonal, and the medial-most electrode was superior. Placement for the SL was determined by placing a tape measure from the fibular head to the heel, with the belly location being less than ½ the distance of the tape measure from the fibular head. The LG was found by placing the tape measure from the fibular head to the heel, and marking the central point 1/3 of the tape distance from the fibular head. The TA was located by placing the tape measure from the lower margin of the patella to the lateral malleolus. The central point is 1/3 from the patella. The VL was located 3-5cm from the superior border of the patella during standing. The BF was located by placing the tape measure from the ischial tuberosity to the lateral epicondyle of the tibia while standing. The central point of the BF was ½ the distance of the tape measure at these locations. Finally, the RF was found by placing the tape measure from the anterior superior iliac spine to the superior border of the patella. The central point of the muscle belly was located ½ the distance of the tape measure. In addition to these muscles, I marked a location on the shin for the ground (Cram & Kasman, 1998).

I marked each location with a permanent marker, and lightly sandpapered each of the markings to reduce interference. Next, I applied a small amount of rubbing alcohol to each location to ensure a clean area for accurate readings. Next, I placed two surface electrodes on each of the located muscle bellies. The electrodes were positioned with 2cm bipolar spacing, and were angled with the direction of the muscle fibers for the most accurate signals. I placed only one surface electrode on the area of the shin marked as the ground. All electrodes were pressed firmly onto the skin to prevent detachment during the trial.

I attached lead lines to all surface electrodes, and gathered them neatly along the participant's leg. Next, I had the participants tuck their shirts into their shorts, and I fed the lead lines between the participant's spandex and shorts. With the bundle of electrode wires now at the top of the waist band, I used a roll of pre-wrap around the entire waist to keep the shorts and wires against the body. I also bounded the EMG wires and kinematic markers on the lower half of the left leg with a fishnet stocking to prevent movement of the ground wire, thus avoiding noise in the signal. Next, I placed the EMG battery pack around the waist (over the pre-wrap), and secured the pack comfortably, but tight enough to prevent movement during each trial. I inserted each wire into the proper location on the battery pack. Once I plugged the computer wire into the pack, the participant was ready to perform functional tests.

To test the placement of each surface EMG, I had each participant perform different functional tests tailored toward that particular muscle. To test the SL and LG, the participant stood on his or her toes. To test the TA, the participant rocked back onto his or her heels, while lifting the toes off of the ground. To test the quadriceps muscles (VL and RF), the participant stood on the right leg and was told to fully extend the left knee and tighten the left thigh muscles. Next, the participant then flexed the knee to test the BF. To test the ADL, the participant pushed the inside of the foot into a wall, as if bringing the foot towards the body. Lastly, I tested the TFL by having the participant push the outside of the foot against a wall, as if pushing the foot away from the body. These functional tests ensured that each of the EMG placements was correct, and that the ground was also placed in a way that eliminated as much noise as possible.

If all functional tests exhibited the appropriate muscle activity, the participant was ready to step onto the treadmill. In order to test metabolic activity during each trial, each participant wore a VO_2 mask and a nose clip during the trial. Once the mask was fitted and the nose clip was placed so that the participant could not breathe through his or her nose, the participant was ready to begin the protocol.

Protocol

The electromyographic, metabolic, and kinematic changes associated with human locomotion have been thoroughly and repeatedly investigated for years. Studies have examined the effects of several different types of human movement, most notably, walking and running, on different graded surfaces. These surfaces, however, have been limited to the sagittal plane, with a specific emphasis towards movement on an up or downhill slope. Therefore, this study will take into account the effects of running in the frontal plane by measuring changes with left and right lateral roll.

Prior to the running trials, each participant completed a seven minute quiet standing trial in order to obtain baseline metabolic information. The participant stood on a level treadmill with arms crossed about the chest. Once the standing trial was complete, I paused the metabolic data collection and administered a five-minute trial in which only electromyography and kinematic variables were collected.

For this five-minute trial, the participant ran at a 3m/s pace for one minute at five different slopes. The different slopes included a ground-level (0°) trial, 3° to the left (left roll), 3° to the right (right roll), 3° upwards, and 3° downwards. The order in which these uphill were administered was randomized for each participant.

I used high resolution cameras, specifically, a 3D photogrammetry system (Motion Analysis Corporation, Santa Rosa, CA) to collect all kinematic data. While recording the running patterns of each participant, I simultaneously recorded the muscle activity for the eight different muscles using the previously mentioned surface electrodes and battery pack (Noraxon U.S.A.: Surface Electromyography, Scottsdale, AZ). This allowed me to match the EMG data from each muscle to the appropriate gait phase. Muscle activity was measured for each of the seven gait phases: initial stance, mid-stance, late stance, terminal stance, initial swing, mid-swing, and terminal swing. For each slope condition, I collected data for two 25s intervals. Therefore, I essentially collected data for 50 of the 60 seconds at each slope. I did not collect metabolic information for this portion of the protocol, but the participant still wore the VO_2 mask in order to acclimate to the different breathing.

Initially, I planned to record electromyographic and kinematic data for the entire duration of the experiment, but realized shortly after the first participant that this would not be feasible. As the experiment proceeded, and the participant began to sweat, there were problems with reflective markers and surface electrodes falling off of the participant. This became extremely problematic as I proceeded to collect EMG and kinematic data throughout the entire experiment, so I modified the protocol by separating the data collections. Furthermore, I placed fans in front of and behind the treadmill, in order to reduce sweat rates to increase the likelihood that the reflective markers and surface electrodes would remain fixed.

Following this five minute trial, I quickly removed the battery pack, all surface electrodes, EMG wires, and reflective kinematic markers. For the remainder of the study, I was primarily concerned with collecting metabolic data (ParvoMedics, Sandy, UT).

Once all but the VO_2 mask and nose clip were removed, the participant completed seven minutes at each of the five different slopes previously mentioned. The order in which the participant ran on each slope was the same as the previously randomized five-minute trial.

Between trials, the participant was asked to hold onto the side rails while I started and stopped the treadmill. I used a level to adjust the slope, ensuring that the angle was correct. The mask and nose clip were not removed during this period. The participant was given a five-minute rest period after the first three seven-minute periods. During this brief rest period, the participant was able to step off of the treadmill and remove the mask and nose clip to get a drink of water.

Statistical Analysis

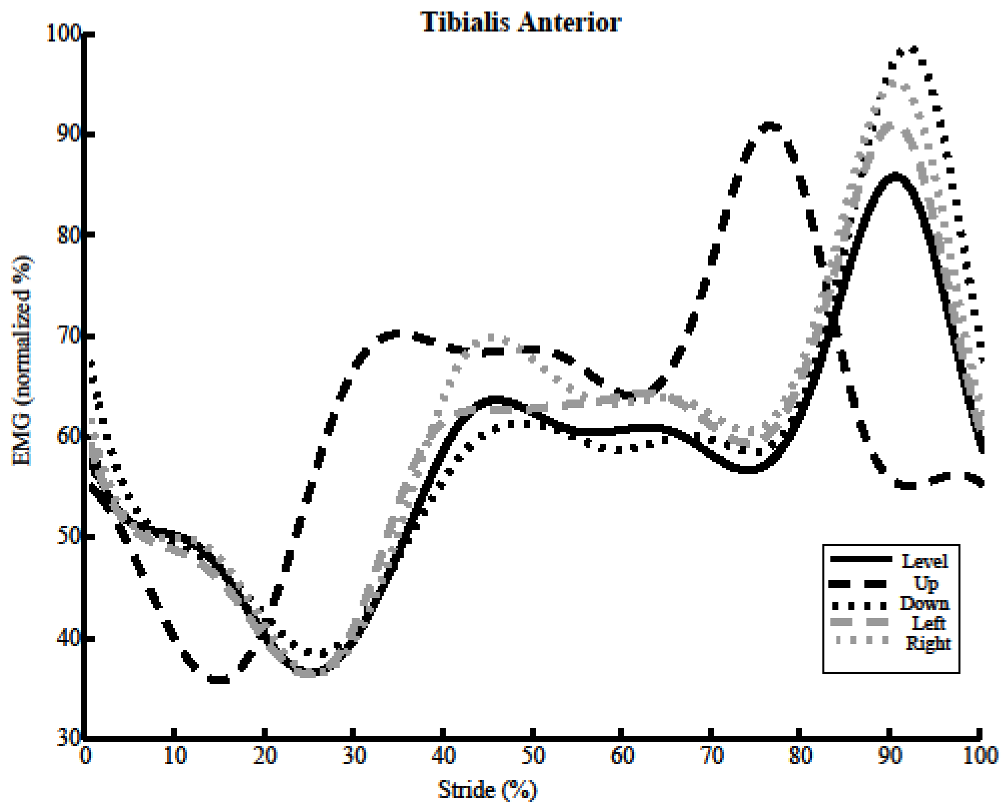
I analyzed the EMG, kinematic, and metabolic data for each participant following the completion of the protocol. I used repeated measures of ANOVA to determine values for EMG and kinematic (spatial-temporal) parameters. If there was a significant difference between conditions, I did a Newman-Keuls post hoc test to obtain more specific values. I used a paired t-test to determine significant differences in the metabolic rates between slopes. I used a significance value of $p < 0.05$ for all data analysis.

CHAPTER 3
RESULTS

Electromyography

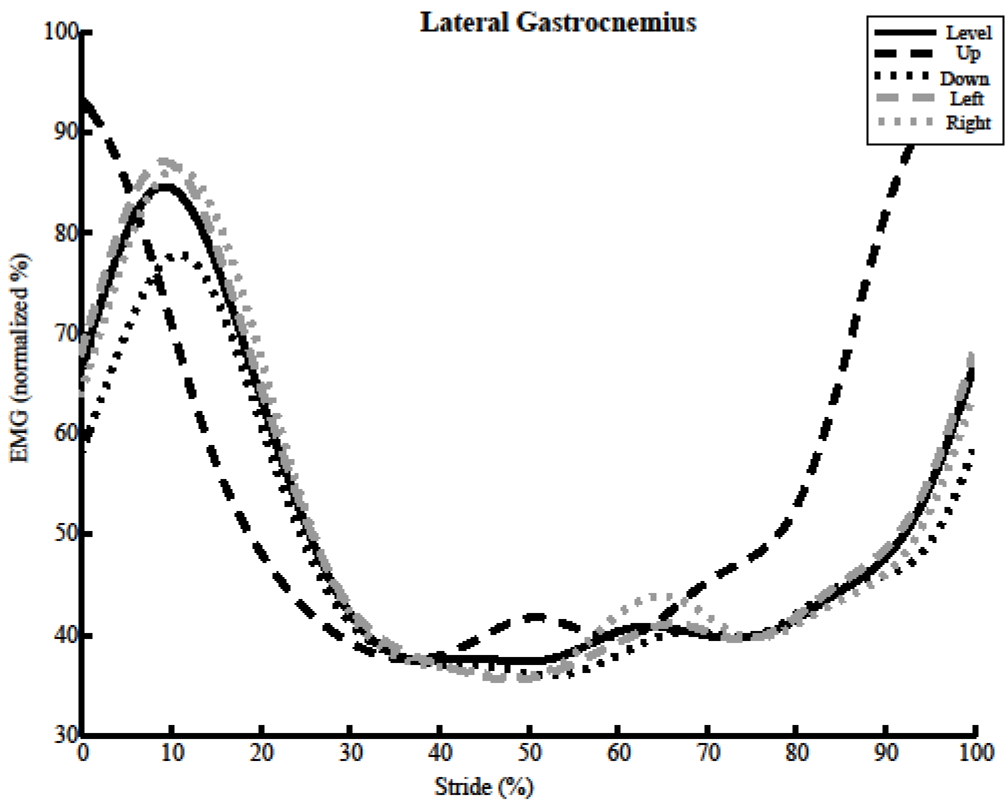
The EMG results depict several statistically significant differences in muscle activity relative to particular muscles, gait phases, and slope conditions.

The EMG activity of the TA relative to each condition is denoted by Graph 1. The TA exhibits significantly less activity during both the initial and midstance phases for uphill running compared to all other conditions ($p < 0.05$). Compared to level running, the activity of the TA during uphill running is 29.5% and 37.5% lower, respectively. Alternatively, the TA exhibits significant increases in muscle activity for both the initial and mid-swing phases for uphill running compared to all other conditions. The level of initial and mid-swing TA activity for uphill running is 46.7% and 70.7% greater than level running, respectively. To add, although these values do not possess statistical significance, it is worth mentioning that the TA activity is consistently lower for left roll compared to right roll, throughout the entire gait cycle.



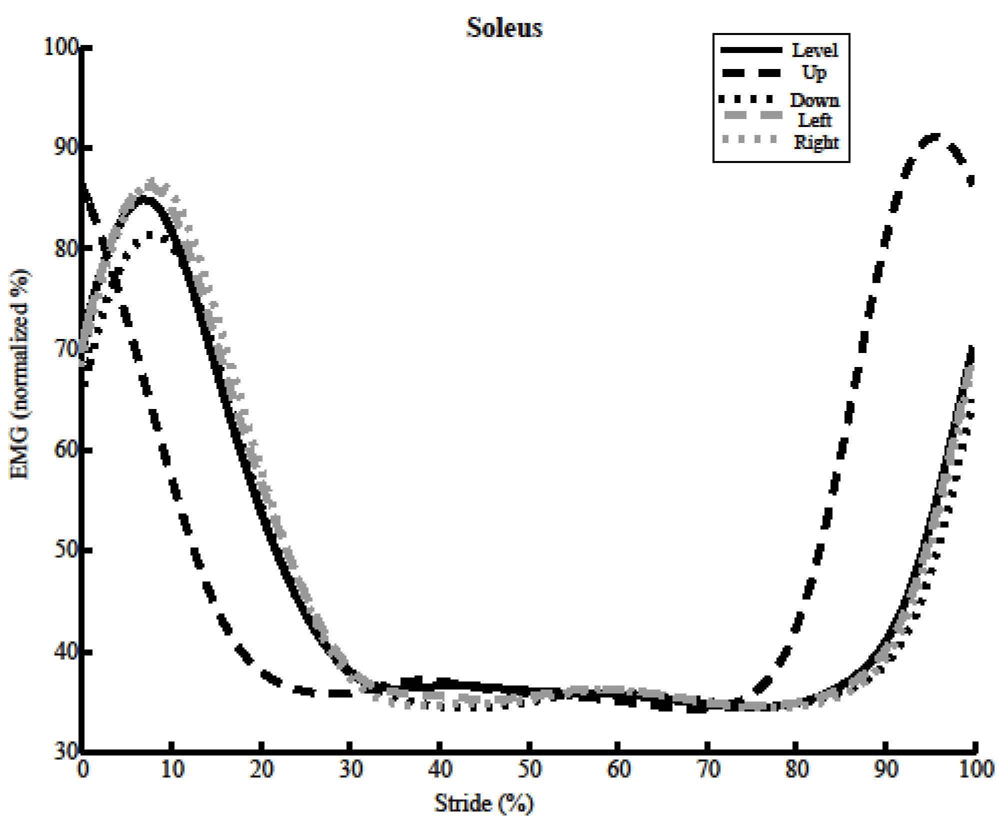
Graph 1. Muscle activity of the TA during each running condition relative to the gait cycle.

The changes in EMG activity of the LG for each condition are presented in Graph 2. The LG demonstrates significantly less activity during the midstance phase for uphill running compared to all other conditions ($p < .05$). Specifically, the activity of the LG during midstance for the uphill condition is 34.8% lower than that of the level. Contrary to stance, there is greater LG activity for uphill running during all phases of swing, but only initial and terminal swing show statistically significant differences. These increases are 44.2% and 216.6%, respectively, for initial and terminal swing LG activity compared to level running. Additionally, despite the fact that these findings are not statistically significant, it should be noted that there are slight differences in LG activity between the left and right roll conditions. During midstance, the LG activity in right roll was 5.1% greater than that of left roll. Conversely, the LG activity in left roll was 11.8% greater than that of right roll during late stance.



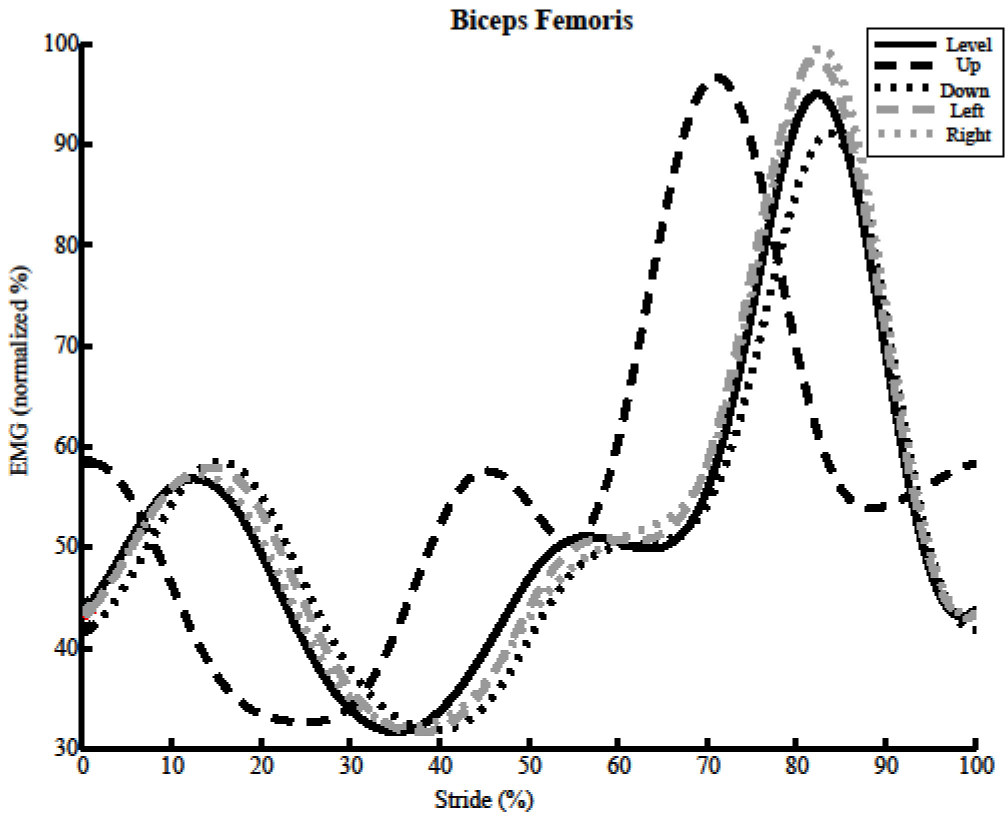
Graph 2. Muscle activity of the LG during each running condition relative to the gait cycle.

The patterns in muscle activity for the SL are represented by Graph 3, and appear to be very similar to those of the LG. The SL exhibits significantly lower activity for uphill running during stance (with the exception of terminal stance), compared to the other conditions. Compared to level running, SL activity is 29.4%, 48.2%, and 35.8% lower for uphill running during initial, mid, and late stance, respectively. Alternatively, there is significantly greater SL muscle activity for uphill running throughout the entire swing phase. Most notably, compared to level, the SL exhibits a 273.7% greater level of activity for uphill running during terminal swing. Moreover, consistent with patterns exhibited by LG muscle activity, there are insignificant, yet noteworthy, differences in SL activity for left and right roll during midstance and late stance. During midstance, the SL activity for right roll was 3.52% greater than left roll, while the SL activity for left roll was 5.1% greater than right roll during late stance.



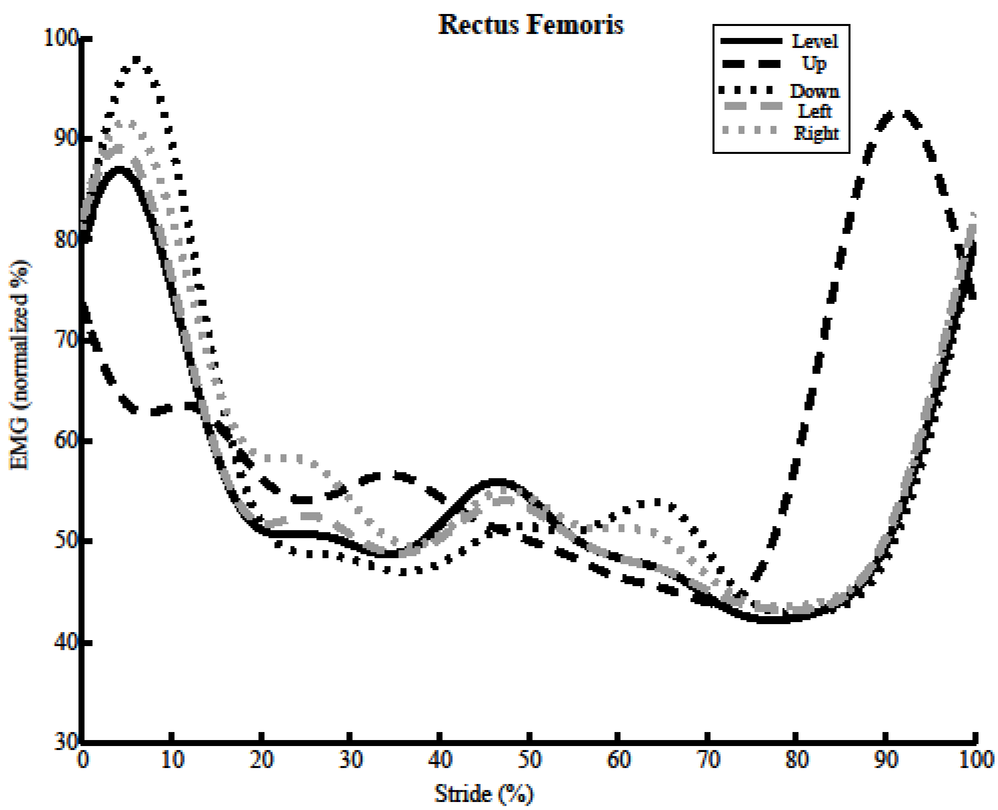
Graph 3. Muscle activity of the SL during each running condition relative to the gait cycle.

The BF also demonstrates significant changes in muscle activity levels throughout the different phases of the gait cycle. These changes are shown by Graph 4, and are representative of each slope condition. During both midstance and late stance, muscle activity levels for the BF decrease significantly for uphill running compared to all other conditions. These levels decreased by 44.6% and 36.2%, with respect to midstance and late stance, compared to level running. It is also worth mentioning that there is a higher level of BF muscle activity during left roll compared to right roll for both midstance (5.6% greater) and late stance (10.0% greater), although this trend is not statistically significant ($p = .29$). Consistent with previous research (Elliot & Blanksby, 1979), I recorded a very large burst of activity in the BF during the initial swing (toe-off) phase. The level of BF activity for the initial swing phase during uphill running was significantly greater than BF activity recorded at this time for all other conditions. Specifically, initial swing BF activity during uphill running was 30.14% greater than what was observed with level running. The same trend is true with mid-swing; however, BF activity for uphill running was 90.3% greater than level running.



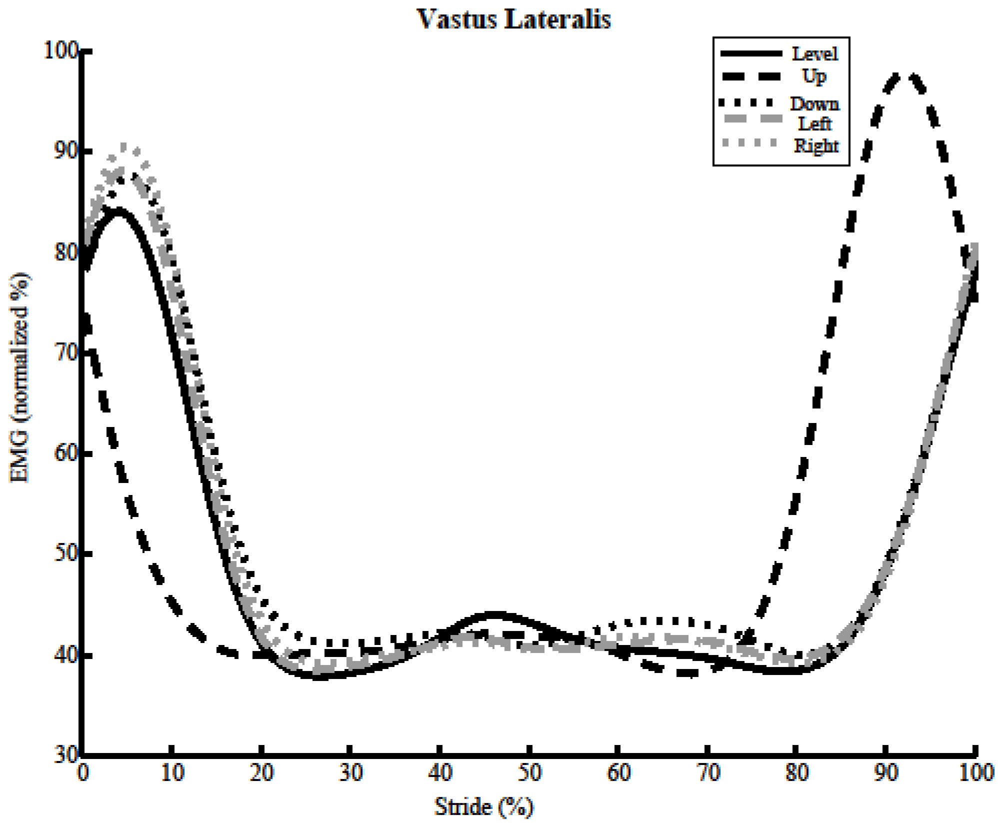
Graph 4. Muscle activity of the BF during each running condition relative to gait cycle,

As shown by Graph 5, there are several significant differences in activity levels for the RF with respect to change in slope. First, there is a significant decrease in RF activity during the initial stance phase of uphill running compared to all conditions. Specifically, the RF is 50.3% less active during the initial stance phase of uphill running compared to level. Also, the magnitude of RF activity (during initial stance) for downhill running is 21.2% greater than that of level running. Another significant difference in RF activity during initial stance can be seen with downhill running compared to left roll. The level of RF activity is 17% greater during downhill running, compared to that of left roll. Yet another instance for which the RF exhibits significant differences in activity between slopes is the initial swing phase. There is a significant increase in RF activity for uphill running compared to all other conditions. Specifically, during the uphill condition, the RF is 40.7% more active than with level running. Finally, I can see that RF activity is significantly greater with uphill slopes during the terminal swing phase. In fact, RF activity during this phase is 143.8% greater for uphill running compared to level running.



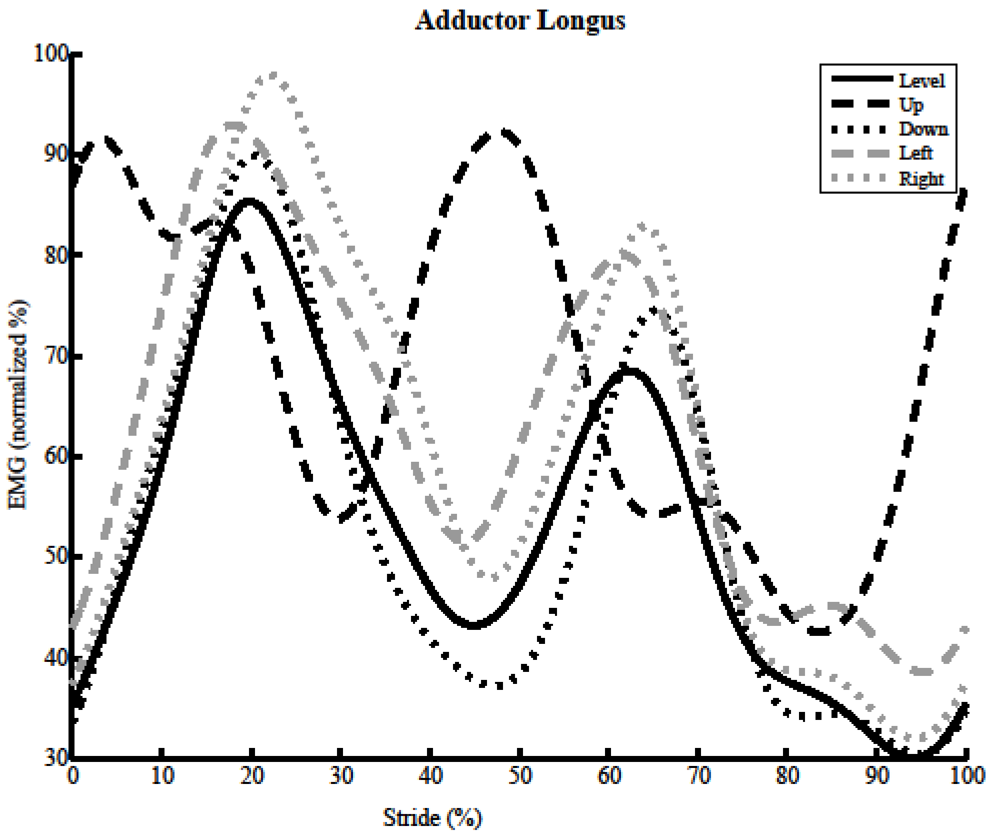
Graph 5. Muscle activity of the RF during each running condition relative to the gait cycle.

Changes in muscle activity for the VL with respect to each slope condition are depicted in Graph 6. Compared to the RF, similar trends in muscle activity are seen in the VL for each slope condition with respect to different phases of the gait cycle. Like the RF, the VL is a member of the quadriceps muscle group, and is involved in knee extension and stabilization during locomotion (Mann & Hagy, 1980a; 1980b). Consistent with patterns of the RF, there is a significant decrease in VL activity during the initial stance phase of uphill running compared to all conditions. Specifically, the VL is 46.7% less active during the initial stance phase of uphill running compared to level. This is also true for midstance, where the activity of the VL during uphill running is 51.3% less than that of level running. Interestingly, during late stance, the activity of the VL with downhill running is significantly greater than both the uphill and right roll conditions ($p < .05$). Lastly, the VL shows significantly greater levels of activity in the uphill condition during terminal swing compared to all other conditions. Specifically, the VL activity of uphill running during terminal swing is 183.3% greater than that of level running.



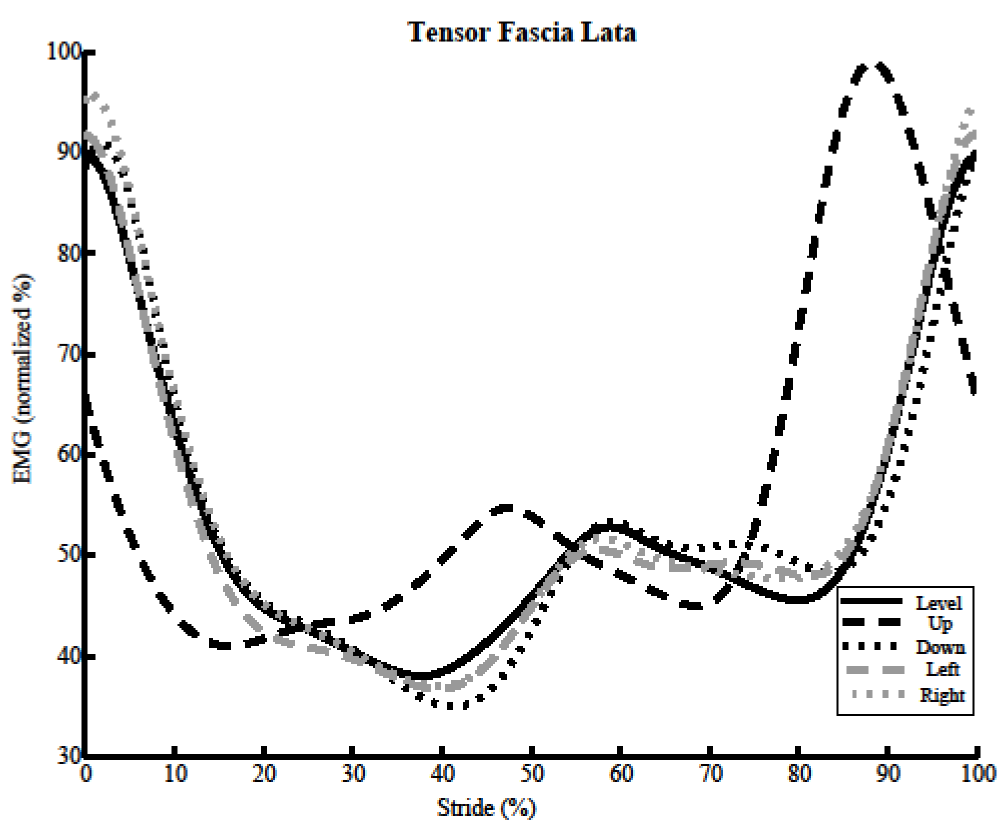
Graph 6. Muscle activity of the VL during each running condition relative to the gait cycle.

The EMG data for the ADL is shown in Graph 7. This data indicates many interesting findings with respect to different slope conditions throughout the gait cycle. During initial stance, the ADL activity for uphill running is 67.2% greater than that of level running. It is also worth noting that left roll running exhibits 10.2% greater ADL activity than right roll running for initial stance, although this difference is not statistically significant. Furthermore, it is proven with statistical significance that ADL activity for right roll is 60.0% greater than uphill running during the late stance phase. It is also worth mentioning that ADL activity for right roll running during late stance is 7.3% greater than that of left roll running, but this difference is not significant. During the initial swing phase, ADL activity for uphill running is significantly greater than all other conditions. Specifically, the ADL is 78.6% more active during uphill running compared to level running. Also during initial swing, the ADL activity during left roll appears to be 11.8% greater than right roll, however, this measure is not significant. Finally, the ADL activity of uphill running is significantly greater than all subsequent conditions during the terminal swing phase. The ADL activity during terminal swing is 95.5% greater for uphill running compared to level running.



Graph 7. Muscle activity of the ADL during each running condition relative to the gait cycle.

The EMG data for the TFL is represented by Graph 8. The TFL was the final muscle that I observed. During the initial stance phase, I found significantly less activity for uphill running. The activity of the TFL decreased by 54% compared to the activity for level running. I also noticed a slight difference in TFL activity between the left and right roll for initial stance. There was a slightly greater magnitude of activity (9.7%) during right roll, but this difference was not significant. During late stance, I observed significantly less activity in the TFL for uphill running compared to all other running conditions. According to my data, the level of TFL activity for uphill running decreased from that of level running by 21.4%.



Graph 8. Muscle activity of the TFL during each running condition relative to the gait cycle.

Metabolics

The average changes in VO_2 associated with each seven minute trial can be seen in Figure 1. The average metabolic rate among the participants during the seven minute standing trial was 5.14 ± .96 $ml \cdot kg^{-1} \cdot min^{-1}$. This value was far less than that of the other trials seeing as it was recorded for the purpose of attaining a baseline metabolic value for each participant at rest. The average metabolic rate for level running was 34.96 ± 3.79$ml \cdot kg^{-1} \cdot min^{-1}$.

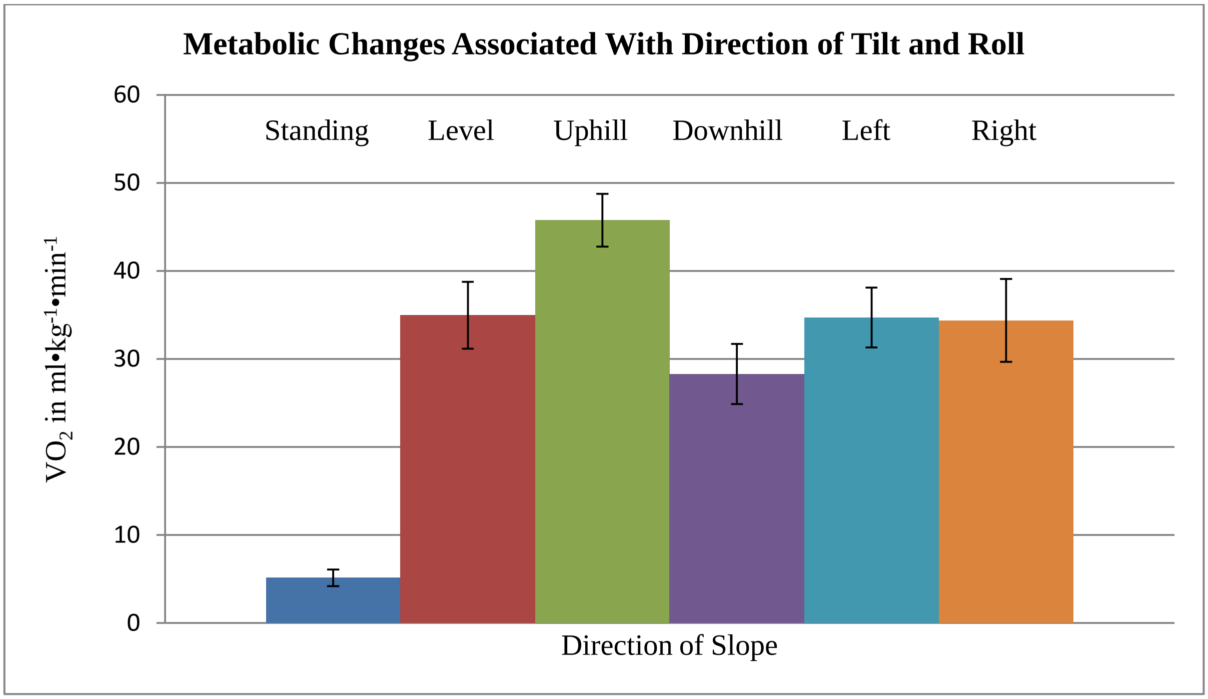


Figure 1. This graph represents the participant averages and standard deviations for metabolic cost associated with each seven minute trial.

In support of my hypothesis, compared to level running, metabolic rate increased for all participants during uphill running. The average metabolic rate for a 3° slope at a speed of 3.0 m/s was 45.75 ± 3.00 ml•kg^{-1}•min^{-1}. It must be noted, however, that 2 of the 15 participants were unable to complete the uphill trial, so the given value is the average oxygen uptake for only 13 participants.

Also in agreement with my hypothesis, as well as previous literature, metabolic rate decreased for all participants during downhill running. The average metabolic rate for a -3° slope at a speed of 3.0 m/s was 28.28 ± 3.42 ml•kg^{-1}•min^{-1}.

Additionally, left roll and right roll exhibited fairly similar average metabolic work values: 34.70 ± 3.39 ml•kg^{-1}•min^{-1} and 34.36 ± 4.71 ml•kg^{-1}•min^{-1}, respectively. These findings support my hypothesis that metabolic work associated with frontal roll would be greater than that of downhill running. Moreover, these findings also support my hypothesis that roll running will require less metabolic work than uphill running.

Finally, the metabolic work associated with roll running is very similar to that of level running. This data is inconsistent with my hypothesis that running on a frontal roll of 3° (both left and right slopes) would require greater metabolic work compared to level running.

Kinematics

The results for the spatial-temporal gait parameters for each slope condition can be found in Table 1, below. From this table, I can see that there are several significant* changes observed for uphill running, while very few significant differences can be seen with downhill or roll running in either direction.

Variable	**Slope Condition**			
	Up	Down	Left	Right
Total Stride Time (ms)	**98.177**	100.75	99.579	99.260
Swing Time (ms)	**119.10**	96.803	99.585	98.065
Stance Time (ms)	**72.853**	**105.73**	99.635	100.82
Step Length	**74.632**	102.46	99.841	98.432
Ankle Step Width (mm)	108.79	107.09	100.38	100.77
Toe Step Width (mm)	87.058	92.374	93.399	78.356

Table 1. This table represents the normalized averages for each spatial-temporal variable for all slope conditions compared to level. The bolded values represent those that were statistically significant from the level.

First, there is a significant decrease in total stride time for uphill running compared to all other conditions. To add, there is a significantly lower total stride time for right roll compared to downhill running; however, this value is not bolded because it only exhibits a significant difference between two conditions.

As noted by Table 1, there was a significantly greater swing time for the uphill running condition ($p < .0001$) compared to all conditions. The swing time for the uphill condition is 19.1% greater compared to that of the level. Contrary to findings by Lay et al., there was no significant increase in swing time observed for downhill running. In fact, there was actually a slight *decrease*, but this observation is not significant. To add, there was no significant change in aerial time (swing phase) with roll running, which disagrees with my hypothesis that the lower leg (right leg is lower during left roll, and left leg is lower during right roll) would experience an increased swing time. Like that of the downhill slope, there is a slight decrease in swing time for both roll conditions compared to level, however, these differences are not consistent enough for drawing any significant conclusions.

Additionally, both uphill and downhill slope conditions show a significant change in stance time compared to all other conditions ($p < .05$). The stance time for the uphill slope decreases by 37.3% compared to the level. Stance time for the downhill slope is about 5.73% greater compared to level. Neither of the roll conditions shows significant changes in stance time compared to level running.

Only a significant change in step length for the uphill condition was found, compared to all other slopes ($p < .0001$). The step length for 3° uphill was 34.0% less than that of the level condition. Additionally, it is worth mentioning that the step length for 3° downhill was somewhat greater than that of the level; 3° to the left was very similar to the level; and 3° to the right was somewhat less than the level. None of these changes are statistically significant; however, it is interesting to note the inconsistency between the left and right roll conditions.

Table 1 also shows that there is an increase in ankle step width for both uphill and downhill running. In fact, this increase is statistically significant for a 3° slope compared to all conditions, except for the -3° downhill slope. Specifically, this ankle step width is 8.8% greater than that of level running. Downhill ankle step width is also significantly greater than roll running in either direction (about 7.1% greater), but shows no significant differences from level or uphill running. To add, there are no statistically significant differences in toe step width for any of the slope conditions. These results disagree with my hypothesis that I would see an increase in step width during roll running as a means for increasing the base of support. It is, however, interesting to note that the left roll shows slightly greater (although not significant) toe step width (19.2% greater) than the right roll.

CHAPTER 4:
DISCUSSION

Based upon my results for EMG, metabolic, and kinematic changes with running on each 3° slope, it is evident that there are several changes in muscle activity, temporal-spatial parameters, and VO_2 for sloped running. Most of these changes are statistically significant for uphill slopes only, which can likely be attributed to the small gradient used for the slope conditions. Overall, for uphill running, there was a significant decrease muscle activity during stance and a significant increase in muscle activity during swing. There was also a significantly greater metabolic cost with uphill running, and a significantly lower cost for downhill. Finally, there was a significant decrease in stride time, stance time, and step length, for uphill running.

Electromyography

The previously discussed EMG analysis incorporated eight lower extremity muscles: TA, LG, SL, BF, RF, VL, ADL, and TFL. Each of these muscles has a fundamental role in producing effective patterns of human locomotion. By interpreting the raw EMG data (Graphs 1-8), and the percentages of change in muscle activity associated with each slope condition, I can draw several significant conclusions. I can also propose possible answers to the unknown, while simultaneously presenting ideas for future research applications.

Because the TA is primarily acting to lower the foot (eccentric contraction) during initial stance, it seems reasonable that the activity observed during an uphill slope would be less than the other conditions. The surface is slanted in such a way that it naturally decreases the angle between the shank and the foot, thus limiting the extent to which an eccentric contraction can occur. Also, the increased activity of the TA for uphill running during initial and mid-swing is consistent with the need for increased ankle flexion in order for the foot to obtain clearance about the upward-tilted surface.

Although there are inconsistent findings pertaining to statistical significance in LG activity for the roll conditions, these patterns have potential implications for more advanced EMG analysis. Because the SL exhibits the same apparent pattern of altered muscle activity between left and right roll during midstance and late stance, I have an even stronger means for investigating this trend further. The LG and SL are also similar in that the greatest difference in magnitude of activity for uphill running compared to level was during terminal swing. This is very interesting, because according to previous literature, the greatest eccentric contraction occurs (in both the LG and SL) during terminal swing in order to stabilize the foot for heel strike (Elliot & Blanksby, 1979). It seems reasonable that the magnitude of this contraction would be greatest during uphill running, compared to other conditions. This can be attributed to the smaller angle between the foot and the shank on uphill surfaces, and thus, a greater eccentric *stretch* about the LG and SL to prepare for heel strike. Previous literature has also stated that the greatest magnitude of concentric contraction for both the LG and the SL occurs at terminal stance in order to assist with ankle extension (Elliot & Blanksby, 1979). Interestingly, there are no statistically significant differences in muscle activity or the magnitude of contraction during terminal stance for either of these muscles. This is rather perplexing, considering the multitude of significant differences with LG and SL activity during other phases of the gait pattern.

Likewise, another seemingly important pattern in SL muscle activity is the consistently greater SL activity during left roll compared to right roll throughout the entire swing phase. Unfortunately, these values are not proven statistically significant on a mere 3° roll, however, this discovery provides implications that steeper frontal rolls may significantly affect the level of SL muscle activity recruited during gait patterns.

The BF undergoes maximal concentric contractions during the late stance phase of gait in order to prepare for knee flexion and hip extension at toe-off (Schwab et al., 1983). With this in mind, it is conceivable that the BF would undergo significant decreases in muscle activity for uphill running during this phase. Because the running surface is sloped upwards, the BF would have to work less to lift the back foot from the slope (e.g., less hip extension), making for an easier transition into swing phase, and thus engaging less BF muscle activity. These findings agree with previous literature stating that a decrease in BF activity was observed during the contact phase (Slawinski et al., 2008). Furthermore, although the findings regarding BF relative to frontal plane roll running are not statistically significant, it is possible that I may find conclusive information about these trends with further investigation. If I were to increase the gradient for each roll, I may have significant evidence for confirming the potential trend that BF activity is greater during left roll running compared to right roll running for both mid and late stance. Additionally, as evidenced by statistical significance, I found that BF muscle activity increases progressively through initial and mid-swing. This is especially true for uphill running, where the magnitude of activity increases from values 30.14% greater than level (during initial swing), to 90.3% greater than level (during mid-swing). These findings agree with previous literature, stating that eccentric contractions increase throughout the early swing phase in order to decelerate hip flexion and control knee extension (Schwab et al., 1983).

The increased level of RF activity for downhill running during the initial stance phase can be seen as a safety-like ‘braking’ mechanism used to slow the body down during downhill locomotion (Dick & Cavanagh, 1987). To add, the significant changes in RF activity during the initial swing phase may be attributed to the aforementioned secondary burst of activity characterized by hip flexion. This increased activity seen with uphill running can, therefore, be explained by the fact that the hip will need to initiate greater flexion so that the foot will clear the upward tilt of the running surface. I can also assume that the high magnitude of RF activity for uphill running during terminal swing is likely due to the primary burst associated with knee extension in order to prepare for stance. Additionally, the changes in RF activity with changing slopes may be associated with an increased need for maintain forward trunk lean for stability purposes.

The VL displays similar trends in activity to the RF during the initial and mid-stance phases of the gait cycle. The activity of the VL is different, however, from that of the RF during late stance. It is statistically significant that, during late stance, downhill running exhibits a greater magnitude of VL activity compared to the uphill and right roll conditions. It is interesting to note that downhill running is not significantly different from the left roll condition, however, this condition is nearly significant ($p = .069$). Aside from the slight difference between left and right roll during late stance, the values for each of the roll conditions are very similar with respect to VL activity throughout the duration of the gait cycle. Finally, the most significant increases in VL activity for uphill running appear during the terminal swing phase. The muscle activity patterns demonstrated by the VL are closely related to the activity patterns of the RF. It is reasonable to attribute these similarities to the crucial role in which both the RF and the VL play in knee extension, thereby exhibiting parallel changes throughout the course of the gait cycle. Please note, however, that unlike the RF, the VL does *not* cross the hip joint (Nilsson et al., 1985). This means that the secondary burst of muscle activity associated with hip flexion during initial swing is unique to the RF.

Our EMG results for the ADL give valuable insight to future implications for running on a frontal plane roll. Although it is widely accepted by previous literature (Mann & Hagy, 1980a) that the ADL exhibits continuous activity throughout the gait cycle, I can use this data to confirm that altering the direction of slope has significant effects on levels of ADL activity relative to different gait phases. I observed increased ADL activity with a positive slope during initial stance; however, this was only significant compared to the level condition. I also noticed several interesting differences between left and right roll throughout the gait cycle, however, none of these trends were proven statistically significant. First, I observed greater ADL activity for left roll (compared to right) during initial stance. During late stance, this pattern was reversed between the two conditions, and I observed greater ADL for right roll compared to left roll. Finally, I observed this reversal once more during initial swing, where ADL activity for left roll running was greater than right roll running. It is possible that these trends are, in fact, accurate depictions of ADL muscle activity, but the significance of these conclusions are being masked by the mere 3° roll angle.

The TFL is a very complex muscle, composed of two different fiber types with two different functions (Mann & Hagy, 1980a), as previously discussed. According to past literature, the posterolateral (PL) fibers are active during initial stance to assist with hip internal rotation. As evidenced by my results, there is a significant decrease in TFL activity during initial stance with uphill running. This brings me to conclude that the level of internal hip rotation decreases during initial stance for the uphill running condition. Likewise, the anteromedial (AM) fibers of the TFL are active during late stance, where they assist with hip flexion. Despite previous findings concluding that this activity can only be observed with high speeds (MacIntyre et al., 1987), my data report significant changes in TFL activity during this phase. This presents implications contrary to previous literature. Perhaps this secondary burst, characterized by activation of the AM fibers, occurs not only with high speeds, but also with grade changes. Moreover, as proven by my data, there is a significant decrease in TFL activity during late stance with uphill running. From this, I can conclude that the level of hip flexion decreases during late stance with uphill running. Finally, although differences between left and right roll for initial stance were not significant, this observation supports my hypothesis for greater TFL activity during a right roll. I hypothesized an increase in TFL activity during right roll, as a means of providing greater stability. With further investigation, I may be able to prove this hypothesis true.

In conclusion, I can make several definitive conclusions about muscle activity changes for the different slope conditions. Several other trends that I observed, however do not present enough conclusive evidence to deem these patterns accurate. Despite being statistically insignificant, many of the observations I have made present grounds for making important conclusions about changes in muscle activity relative to frontal plane roll. Perhaps the patterns I observed between right and left roll indicate that with steeper roll angles, I will see significant differences. In order to determine whether these patterns are realistic, I must manipulate the steepness of the roll angle for each slope condition.

Metabolic Activity

The results I obtained from this experiment show that young, healthy runners exhibit oxygen uptake patterns consistent with previous implications when running on a sagittal plane tilt, but are somewhat inconclusive regarding frontal plane roll.

First, I found many similarities between my data and previous literature concerning an upward tilt in the sagittal plane. My results supported previous claims stating that uphill running is more costly than level running of the same speed (Klein et al., 1997; Minetti, 2001). In fact, by increasing the slope to +3°, I found that VO_2 significantly increased an average of 23.6% compared to level ($p < 0.05$). Increasing the grade during uphill running also increases the activity of muscles directly involved with running patterns (Williams, 1990). This results in an increased metabolic demand to those muscles, which is consistent with the increased ATP demands for muscular contractions (Volkov et al., 1975). As previously stated, the oxygen we inhale is carried through the bloodstream, and is directly involved with the creation of this crucial compound (Padykula et al., 1955), so it seems reasonable that increasing ATP demands will also increase oxygen demands.

Also consistent with previous research, I noticed a decreased average rate of oxygen uptake for downhill running. My results showed that VO_2 decreased significantly, by 19.1%, when running on a -3° slope compared to level ($p < 0.05$). A decreased rate of uptake may be attributed to a decrease in muscle activity, or perhaps a change in the type of muscle contraction used for locomotion. According to previous literature, an eccentric muscular contraction requires 3 to 5 times less energy than a concentric contraction of the same muscle (Saltin, 1973). A transition from concentric contractions to predominately eccentric contractions would lessen the demand for oxygen to the muscles, thereby decreasing the rate of uptake.

Seeing as there is a substantial amount of conclusive evidence for uphill and downhill running, the main focus of this experiment was to determine the changes in metabolic rate that occur with running on a frontal plane roll. My hypothesis that roll running would increase metabolic demand compared to downhill running was confirmed. Participants running on a 3° roll in either direction (left or right) averaged an 18.5% greater VO_2 compared to running on a -3° downhill slope at the same speed.

To support my hypothesis that roll running would cost less than uphill running, it was proven ($p < 0.05$), that roll running had a significantly lesser metabolic demand compared to uphill running. Each of the 14 participants that completed the uphill trial showed significantly greater VO_2 values when running 3° uphill compared to a 3° roll in both left and right directions. In fact, VO_2 was 24.16% greater with uphill running compared to roll running in the frontal plane.

My hypothesis that running on a frontal plane roll would increase metabolic rate compared to level running was not confirmed. There was no significant difference in VO_2 between either of the roll conditions and the level condition. The similarities in metabolic cost between frontal plane roll-running versus level ground running may be caused by a myriad of factors, many of which future studies may aim to determine.

To conclude, compared to level, the metabolic cost of uphill running was significantly greater and the cost of downhill running was significantly less, but the cost of running on a lateral roll was not significantly different from that of level running. This is consistent with previous literature: propulsion accounts for 52% of metabolic cost, braking accounts for 40%, and stability accounts for only 6% of metabolic cost (Saltin, 1973). This makes sense, seeing as the need for propulsion and braking increase for uphill and downhill running, respectively. Perhaps the need for stability increases for frontal plane roll, but because 6% is a much lower portion of metabolic demand, the gradient used for roll may have been too small to elicit significant changes.

Kinematics

The spatial-temporal parameters that I measured during this experiment include total stride time, swing time, stance time, step length, ankle step width, and toe step width. These parameters are affected by factors including, but certainly not limited to, velocity (Nilsson & Thorstensson, 1985), grade (Davies et al., 1974), footwear (Clarke & Frederick, 1983), anthropometric dimensions (e.g., height, weight, etc.), muscle fiber composition (Heikki et al., 1978), state of fatigue, and countless others.

Unfortunately, very few conclusions can be drawn from the temporal-spatial results for 50 seconds of 3° frontal roll running (in both left and right directions) on a treadmill moving 3m/s. One variable that did, in fact, indicate statistical significance for frontal roll was total stride time. I found that total stride time for a right roll was significantly less than that of downhill running. This indicates that there may be notable changes to gait patterns as a result of roll running. To expand further, I can suggest that these changes are consistent with ideas from previous research. For example, we know that uphill running elicits an increased stride frequency (Dick & Cavanagh, 1987), so perhaps I can infer that running on a roll results in a slight increase to stride frequency compared to downhill running. It is also important to note that stride time for left roll was not significantly different ($p < .05$) from downhill running, however it was very close ($p = .068$), thus, implying only slight differences between left and right roll.

Consistent with the previously mentioned differences in stride time for frontal roll compared to downhill running, I also found statistical significance regarding stance time for a 3° roll and a 3° downhill slope. Stance time for roll running is significantly less ($p < .05$) compared to stance time for downhill running.

Although the statistically significant evidence about running on a frontal roll compared to all other slope conditions was fairly limited, I did find conclusive information pertaining to spatial-temporal changes in response to tilt in the sagittal plane.

Past literature regarding changes accompanying uphill and downhill running has had extremely controversial implications. The results from my experiment support some of these findings, but are inconsistent with others.

Contrary to findings that there were no significant changes to running mechanics when runners (3.55 m/s) were introduced to a 2.9° slope (Klein et al., 1997), my data present several statistically significant ($p < .0001$) changes concerning uphill running.

First, my results provide evidence that a 3° slope elicits a significant decrease in total stride time ($p < .05$), compared to all conditions. These findings agree with my hypothesis that running on an uphill slope would decrease total stride time as a means of compensating for the increased stride frequency that occurs with uphill. Also, swing time for uphill running was significantly greater than all other conditions. Specifically, uphill swing time was 19.1% greater than level running. A decrease in stance time for the uphill slope condition is logical, seeing as there is a significant increase in swing time. It is, however, important to note that the total stride time for uphill running had a *net decrease* compared to that of level running. To maintain this proportion, the decrease in stance time for uphill running (compared to level) should be of greater magnitude than the aforementioned increase in swing time. In support of this constraint, my findings represent a 37.3% decrease in stance time for uphill running compared to level.

In accordance with findings from Dick & Cavanagh, my results indicate a significant decrease in step length for uphill running compared to all conditions. Specifically, uphill step length was 34.0% less compared to level, which agrees with my hypothesis that I would observe a decrease in step length for an uphill slope The decreased step length observed during the uphill condition is likely the result of increasing step frequency in order to compensate for the uphill slope (Dick & Cavanagh, 1987).

I can agree with claims made by Klein et al. that there are no significant changes in running mechanics for downhill running compared to level running, but this does not hold true for downhill running compared to the other slope conditions. I observed significant differences in total stride time between downhill running and frontal roll running, with a much greater stride time for downhill compared to right roll. Furthermore, I hypothesized that there would be an increase in swing time associated with running on a downward slope. Inconsistent with my hypothesis, I observed a slight decrease in swing time for downhill running compared to level, although this difference was not significant. Contrary to swing time, where no significant difference was observed between downhill and level, there was a significant increase in stance time for downhill running compared to all other conditions ($p < .05$). Specifically, stance time for downhill running was 5.73% greater than level running.

Despite the slight differences observed with running on a frontal plane roll compared to subsequent conditions (e.g., greater step length for left roll compared to right and greater toe step width for left compared to right), these differences are not consistent enough for deeming them statistically significant. Although some of these spatial-temporal differences may seem compelling, the standard of error was too high for considering them conclusive. Therefore, it may be beneficial for future investigators to consider possible tactics for resolving this ambiguity prior to future investigation of the kinematic parameters during frontal plane locomotion.

Limitations

Because there is very limited research about running on a frontal plane roll, I aimed to touch briefly on several aspects of running. I created a relatively broad experiment for analyzing muscle activity, metabolic activity, and kinematic activity with respect to left and right roll. Due to the broad nature of this experiment, there were many different variables for which I had to control for.

First, my pool of participants was one of the most important variables that could potentially skew my data if I was not careful. Because one of the major data collections for this experiment was based upon changes in metabolic activity, the process for choosing participants was highly regulated. Aerobic metabolism is extremely sensitive to inter-individual variability. It is affected by everything from age and muscle fiber composition, to psychological states and gait patterns, thus, making it one of the most difficult experimental measures to accurately obtain (Saltin, 1973). Due to the fact that the validity of the metabolic values is affected by such minute detail, I needed to minimize the individual differences between my participants as much as possible; otherwise I ran the risk of skewing my data to such an extent that it became purely irrelevant. For this reason, I wanted to create a sample size with similar characteristics, but also representative of both genders. The inclusion criteria required that all participants were college-aged, with a relatively experienced background in distance running. I defined "experienced" as habitually running 20+ miles per week, including hills, at an 8:00 mile pace. I held preference for cross country members over other volunteers in order to ensure a relatively "fit" aerobic capacity, thereby preventing participants from reaching their VO_2 max during the experiment. There was, however, one female participant who could not continue once she reached the seven minute uphill trial. I was still able to use all of her EMG and kinematic data, as well as all metabolic data up to the point in which the study was terminated. I included this data for the purpose of incorporating as much supporting data as possible, seeing as my sample size was limited to only fifteen participants.

Additionally, not only is metabolic data extremely sensitive to physiological and psychological characteristics pertaining to a particular individual, it is also sensitive to the environment for which that individual is exposed (Hermansen,1973). With this in mind, I must be cautious when analyzing the respiratory exchange rates corresponding to a particular trial condition. To avoid skewing the perceived gas exchange rates of subsequent trials, I omitted the first two minutes of metabolic data from each seven minute trial. By doing so, I am still left with five minutes of solid data for each slope condition, while also providing sufficient time to confirm that all residual gases from the previous trial have been flushed from the tubes. Therefore, by excluding the first two minutes of metabolic data from each trial, I can be sure that I am determining metabolic rates that correspond to the appropriate slope conditions.

While some of the potentially negative confounding variables influencing this study were predictable, there were others with which I did not encounter until I attempted the experiment first hand. As I previously mentioned, I initially planned to record electromyographic and kinematic data for the entire duration of the experiment, but realized that this would not be practical. For this reason, I modified the experiment by separating the EMG and kinematic data collections from metabolic collections. The purpose of the five-minute trial (that followed the baseline standing trial) was to record EMG and kinematic data only: metabolic activity was not recorded, but the VO_2 mask was still worn. There were several advantages and disadvantages to this approach.

This modification was advantageous because I was able to obtain two 25s intervals of solid data for each condition (up, down, level, left, right), and I enhanced the comfort of each participant by removing all EMG and kinematic equipment prior to continuing the metabolic portion of the experiment. Also, I was able to prevent skewing the EMG data in the sense that the muscles were “fresh” rather than fatigued from previous trials. Similarly, this method ensured clean kinematic data as well, because all reflective markers were detected by the cameras, seeing as they did not have time to shift or fall off of the participant.

Conversely, this five-minute trial was disadvantageous because with less data, there is seemingly less reliability. Because EMG and kinematic data was only collected for a total of 50s for each condition, it is likely that I did not record data for an adequate amount of time. A good portion of these recordings were likely devoted to engaging the appropriate muscles and fine-tuning necessary levels of activity by recruiting motor units in some muscles and dismissing them in others. Also, it takes time to modify the spatial-temporal parameters of my stride patterns for adjusting appropriately to the changing slopes. By capturing data from only the first minute of each condition, I ran the risk of over-generalizing these changes, and thereby making false attributions about gait changes relative to the direction of slope.

One last approach that I used to increase the validity of my data was the process of randomization. The order in which I administered each of the conditions to my participants was completely arbitrary. The purpose of randomization was to avoid the possibility of seeing any metabolic trends that resulted from the order of the slope, rather than the slope itself. For each participant, I randomly assigned the order of slope conditions prior to the five minute EMG and kinematic data collection. I used this same order for the subsequent metabolic portion of the study in order to maintain simplicity and consistency with each participant.

Future Research

Because the biomechanical factors and the metabolic activity changes associated with running on frontal plane slopes have received very little attention in past literature, this study leaves many opportunities for further investigation.

With such an abundance of existing literature pertaining to changes in metabolic activity associated with the human body, it seems as though almost any modification to exercise would have pronounced effects. It seems inconceivable that running on a frontal plane slope exhibits insignificant results compared to level running. Because the metabolic activity of running on a frontal plane roll has received very little attention in past literature, it is necessary that this phenomenon be explored further.

Perhaps there is a balance effect between the muscle demands of each leg while running on a 3° roll. Future investigators may obtain more conclusive results by simultaneously recording the EMG activity of both legs while running on frontal plane slopes. This way, one would be able to determine whether there is some compensatory mechanism utilized between the muscles of each limb that seemingly 'masks' any possible differences occurring during frontal plane sloped running. For example, consider the following hypothetical situation: the left leg exerts greater contractile forces and recruits additional motor units for particular muscles during a 3° right roll, and at that same instant, the right leg compensates by exerting smaller contractile forces, or possibly even terminating a particular muscle's activity entirely. If this were proven true, then it could be possible that this compensatory relationship between legs results in a very similar demand for total oxygen to active muscles of the entire lower extremity. Although this particular proposition may not be correct, it creates implications that despite the similar VO_2 values between level and roll running, there may, in fact, be a true difference between these conditions.

Also, in accordance with the disadvantages associated with such short durations of EMG and kinematic data collections, perhaps recording further into each condition would bring light to new information. An extended collection time might allow for the participant to adapt to an ideal gait pattern that allows for the most efficient use of muscle recruitment, etc. In fact, this idea provides implications for future studies, because I can compare these results to data taken later in the experiment (i.e. once participants have had adequate time to adjust to slope conditions, and the muscles have started to fatigue) to determine whether there are major changes that occur throughout the duration of the experiment. I can even expand upon this by recruiting a very large pool of participants, and creating sub-groups which whom I administer the same patterns of slope trials to see if trial order affects the data I obtain.

It would also be beneficial to vary the protocol in a way that explores different variables that alter electromyographic, metabolic, and kinematic function. For example, by varying the speed (i.e. slow, moderately fast, and sprinting) or the degree of the slope (i.e. 3°, 5°, & 7° for each condition), I will have a more concrete means of comparison for discovering changes caused by frontal plane roll. These studies may require a more elaborate protocol, thus taking longer to complete, however, a more thorough investigation is likely to provide new, significant information.

Conclusion

As seen by the results presented for electromyography, metabolic activity, and spatial-temporal parameters, I am able to make very interesting conclusions about running on different slopes. The majority of significant changes I observed for this experiment were with respect to sagittal plane tilt; although I did observe several trends with roll running in which I hope to confirm with further investigation. The major findings (statistically significant; $p < .05$) are summarized below.

In short, I observed significant differences in muscle activity for several muscles during the uphill slope compared to all other conditions ($p < .05$). During stance, I found significantly less activity in the TA, LG, SL, BF, RF, VL, and the TFL. There was significantly greater activity measured in the ADL during stance. During swing, there was significantly more activity in the TA, LG, SL, BF, RF, VL, and the ADL. For the downhill slope, I measured significantly greater RF activity during the stance phase, compared to level and left roll. During late stance, I measured significantly greater VL activity for the downhill condition compared to uphill and right roll. Finally, the ADL activity of right roll during the late stance phase was significantly greater compared to the uphill condition.

Compared to level running, I measured significantly greater levels of metabolic activity for the uphill condition. My results also prove significantly lower levels of metabolic activity for the downhill condition. Left and right roll displayed significantly greater metabolic demands than the downhill condition; very similar metabolic demands compared to level, and significantly lower demands compared to the uphill condition.

In regards to temporal-spatial variables, there is a significant decrease in stride time for uphill, compared to all other conditions. There was also a significantly lower stride time for right roll compared to downhill. There was a significant increase in swing time for uphill running. Conversely, there was a significant decrease in stance time for uphill, as well as a significant increase in stance time for the downhill condition. Step length decreased significantly for uphill running; and I also measured a significant increase in ankle step width for both uphill and downhill slope conditions.

It is commonly known that hills affect a runner's ability to maintain an even race pace, thus interrupting the consistency of his or her running pattern (Wank et al., 1998). Past literature proves that this problem can be controlled through hill training, but unfortunately, hills are not the only terrain issue encountered by runners. The natural terrain contains ditches, potholes, rocks, sidewalk cracks, and endless other gait-altering obstacles. In this case, the runner must initiate the appropriate actions for maintaining a smooth locomotive trajectory and a steady center of mass. This includes the ability to make quick and efficient postural adjustments, as well as activating the appropriate muscles effectively. These compensatory actions are necessary for preventing injury as well as performance hindrance. All of the aforementioned results present a unique perspective to the world of locomotion. Based upon these findings, coaches, trainers, and performance athletes may begin to incorporate gait-altering slopes into their training regimens to determine whether these training methods elicit performance benefits. Perhaps there is, indeed, a way to train the human body to respond to these slope changes in a way that prevents performance hindrance.

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ACADEMIC VITA

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EDUCATION

The Pennsylvania State University, University Park, PA

Bachelor of Science in Kinesiology
Option in Movement Science
Honors in Kinesiology
Graduate May 2011

THESIS

The Effects of Uphill, Downhill, and Lateral Roll Treadmill Running: An EMG, Kinematic, and Metabolic Analysis

Supervised by Jinger S. Gottschall

RELATED EXPERIENCE:

Research Assistant **August 2009- Present**
Penn State Biomechanics Laboratory

- Oversee four other students while directing an experiment for my thesis project
- Prepare participants for study protocol by recording anthropometric measures, applying EMG and kinematic markers, and calibrating metabolic equipment
- Analyze locomotion and gait through the use of cameras and kinematic markers
- Post-process all collected data using EVART software

Teachers Assistant **January 2009- August 2009**
Cadaveric-Based Anatomy Course (Kinesiology 202)

- Directed cadaveric observation and palpation during an anatomy lab session
- Researched a specific anatomy-related participant and compose a case study analysis

Preparation for student observation

- Participated in the removal of all vital organs in the human thorax
- Completed a full body dissection to disclose nerves, muscles, and blood vessels for student-learning purposes
- Performed a cadaveric 'Tommy-John' surgery and an ACL repair using harvested tendons

Research Assistant **January 2008- May 2009**
Women's Health and Exercise Physiology Laboratory (Noll Lab)

- Managed data for laboratory studies
- Handled and aliquoted blood and urine samples
- Prepared test tubes and vials for blood draws and hormone level analysis

PROFESSIONAL SKILLS:

- Strong communication and motivational skills useful for maintaining a positive environment while working with others
- CPR certified; experience with taking vitals and anthropometric measurements
- Skillful with EKG, EMG, and metabolic activity analysis
- Proficient in the use of EVART and MAXTRAQ software for motion and gait analysis

HONORS & AWARDS:

- Dean's List all semesters
- National Honors Society (three yrs.)
- Highest Honors & PTSA recognition (four yrs.)
- Schreyer's Honors College
- All-American Rowing Association: Excellence in Academia

LEADERSHIP AND EXTRACURRICULAR ACTIVITES:

- Penn State Crew
    - Captain of the Women's Varsity squad
- Penn State Kinesiology THON
    - Executive Chair
- Active member of the Penn State Snowboard Club