THE PENNSYLVANIA STATE UNIVERSITY

SCHREYER HONORS COLLEGE

DEPARTMENT OF KINESIOLOGY

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

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Spring 2012

A thesis

submitted in partial fulfillment

of the requirements

for baccalaureate degrees

in Biology and Psychology

with honors in Kinesiology

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ABSTRACT

Much research has been devoted to studying uphill and downhill walking and how they differ from level walking with regard to metabolic cost, muscle activity, and kinematics. However, research has not explored tilt walking (walking on a plane tilted to the left or right) and how it compares to level walking with regard to those same factors. This study focuses on tilt walking in addition to working toward confirming previous findings about uphill and downhill walking. Generally, the findings of this study on uphill and downhill walking agree with the findings presented in previous literature. Because of the lack of previous research on tilt walking, there is no literature to which I can compare the results obtained in this study. Overall, tilt walking was not shown to differ significantly from level walking with regard to metabolic activity, muscle activity, or kinematics. These results did not correspond with my hypotheses; I had initially expected to see significant differences in metabolic activity, the activity of specific muscles, and some gait components. This lack of concordance between my hypotheses and results leaves many questions yet to be answered and defines the necessity for further research regarding tilt walking.

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ACKNOWLEDGEMENTS

Thanks to everyone who made this project possible!

First and foremost, I would like to thank my thesis adviser, Dr. Jinger Gottschall. Without her this project would not have been possible. She was with me every step of the way and provided me with the guidance I needed to be able to complete this project successfully.

Secondly, I would like to thank the undergraduate and graduate students in the Biomechanics Lab who helped with my project. Their efforts are greatly appreciated and were vital to the success of the experiments.

I would also like to thank my family and friends for their constant support. They made me who I am today and instilled in m the confidence I needed to have such success as an undergraduate student.

CHAPTER 1: INTRODUCTION

Practical Significance

Walking on a treadmill is a common method people employ when trying to improve their health (lose weight, gain muscle, make their heart stronger, etc.). As people improve, they can move from walking to running, or they can choose to walk on an incline in order to make the activity more difficult so that they can continue to improve the health of their bodies. Taking this into consideration, perhaps walking on a surface tilted to the left or right would provide a more difficult activity that requires greater muscle activity and metabolic cost, thus enabling individuals to continue to improve their physical capabilities and health. This study will enable me to show whether tilted walking is significantly more difficult than level walking with regard to muscle activity, metabolic cost, and kinematics of gait, thus showing if it would be an effective means of improving physical ability beyond level walking.

Metabolic Activity

<u>Level Walking</u>

The metabolic cost of level walking has been a topic of interest in the past. In a study done by Minetti et al. it was shown that the cost of walking is 1.85±0.57 J kg^{-1} m^{-1} at a 0.69 m/s speed on a level surface (Minetti et al., 2001). Obviously, the metabolic cost on a level surface will vary with the speed so it is imperative that the speed is kept constant when comparing metabolic cost during level walking to metabolic during other conditions.

Hill Walking

In that same study conducted by Minetti et al., it was shown that higher metabolic rates are associated with walking on an uphill slope as compared to a level surface; furthermore, the greater the uphill slope, the greater the metabolic rate (Minetti et al., 2001). This data is consistent across the literature. Evidence of this is that the cost of walking is up to 17.33±1.11 J kg^{-1} m^{-1} at a 0.69 m/s speed on a slope of +0.45 (Minetti et al., 2001).

Minetti et al. also showed that lower metabolic rates are associated with walking on a downhill slope as compare to a level surface; however, as the magnitude of downhill slope increases this effect disappears, and the metabolic rate begins to increase as with uphill slopes. Evidence of this is that the cost of walking drops to 0.81±0.37 J kg^{-1} m^{-1} at a 0.69 m/s speed on a slope of -0.10 but goes up to 3.46±0.95 J kg^{-1} m^{-1} at a 0.69 m/s speed on a slope of -0.45 (Minetti et al., 2001).

Electromyography

Level Walking

The Tibialis Anterior (TA) is most active during late swing to keep the foot dorsiflexed during reach phase. Soon after, its activity peaks producing the force that lowers the foot to the ground. The TA's second burst of activity results in dorsiflexion of the foot for foot clearance during mid swing (Winter, 1991).

The Lateral Gastrocnemius (LG) exhibits one major phase of activity. Activity occurs during stance and reaches its peak at mid push-off, which corresponds to 50%

stride. This muscle lengthens from 5% stride to 40% stride. It, then, shortens during push-off to generate the most important impulse of energy. Activity then drops and the low activity is maintained through the swing (Winter, 1991).

The Soleus (SL) has a single peak of activity at about 50% stride. The muscle is active early in the stride to control the forward rotating leg during stance. It is then active from 40% stride to 60% stride to generate an explosive push-off (Winter, 1991).

The Peroneous Longus (PL) demonstrates two phases of activity. The first phase occurs at 10% stride; here the muscle acts to aid in weight acceptance and stability. The second phase is a large burst that occurs at 50% stride during push-off (Winter, 1991).

The Vastus Lateralis (VL) activity pattern contains only one major peak that occurs at 10% stride during weight acceptance. Its purpose is to control the level of knee flexion and to help in knee extension during mid stance. Some subjects show a second minor peak of activity at about 70% stride. This minor peak is thought to represent this muscle's activity in assisting the RF to decelerate the backward swinging leg and foot (Winter, 1991).

The Biceps Femoris (BF) (lateral hamstring) has one major peak that occurs at 4% of stride. It plays a role in decelerating the leg during swing phase, but is secondary in this action to the Semitendinosus (medial hamstring). It plays a more important role as a hip extensor during weight acceptance (Winter, 1991).

The Adductor Longus (ADL) shows two peaks of activity of about equal magnitude. The first peak occurs at 10% stride during weight acceptance representing a co-contraction to the hip abductors and hip extensors that are highly active during this time. The second peak occurs at about 60% stride; the ADL is active at this point as a hip flexor to aid the RF in accelerating the thigh forward during early swing (Winter, 1991).

The Tensor Fascia Latte (TFL) exhibits a pattern of three decreasing peaks of activity during one stride. The first peak occurs at 15% stride representing its activity in assisting the gluteus medius in controlling the pelvis drop during single foot support. The second peak occurs at about 40% stride during mid to late stance when it is the medial rotator of the hip. The third and final peak occurs shortly before 70% stride during early swing; this peak likely represents the TFL's action as a minor hip flexor (Winter, 1991).

Hill Walking

A study conducted by Lay et al. shows that during uphill walking two of the eight muscles being studied here demonstrate significant increases in mean activity of stance phase bursts as compared to during level walking. The two muscles are the SL and BF. The only muscle that does not have a significant increase in mean activity is TA. The other five muscles examined in this study (LG, PL, VL, ADL, and TFL) were not examined by Lay et al. Furthermore, Lay et al. demonstrate that burst durations of the BF increases progressively during uphill walking (Lay et al., 2007). Previous studies have shown consistent data with regard to the SL (Leroux et al., 1999; Tokuhiro et al., 1985). However, previous data is inconsistent with regard to the findings on the TA; this inconsistency is likely due to the variability of the TA (Lay et al., 2007).

Lay et al. also show that during downhill walking only one of the eight muscles being studied here demonstrate significant increases in mean activity of stance phase bursts as compared to during level walking. The muscle is the TA. The SL and BF do not have significant increases in mean activity. Again, the other five muscles examined in this study (LG, PL, VL, ADL, and TFL) were not examined by Lay et al. Lay el al. also demonstrate that burst durations of the SL increases significantly during downhill walking (Lay et al., 2007). Research with regard to downhill walking is more limited than with regard to uphill walking, but other studies' findings are consistent with those found by Lay et al. (Mitsui et al., 2001; Tokuhiro et al., 1985).

Kinematics

Level Walking

Level walking exhibits a consistent cycle of events regardless of speed. The two events are foot strike and foot off. Stance and swing (the two phases of the gait cycle) can be described using these two events. The first 62% of the gait cycle is the stance phase. The stance phase encompasses the following events: foot strike at 0%, opposite foot off at 12%, opposite foot strike at 50%, and foot off at 62%. The last 38% of the gait cycle is the swing phase. The swing phase encompasses the following events: foot off at 62%, foot clearance, and, finally, foot strike at 100% (Rose et al., 1994).

During level walking, the hip is flexed at initial contact. It then extends until the opposite foot makes contact. At opposite foot strike, the knee and hip flex (Rose et al., 1994).

The knee first flexes during stance phase to help absorb the weight during foot strike. By mid stance, the knee is in a state of extension. The knee flexes for the second time during early swing phase, just before hip flexion. The knee reaches maximum flexion when the swinging foot passes the planted foot allowing for foot clearance by effectively shortening the swinging leg. The knee then begins to extend reaching almost full extension just before foot strike (Rose et al., 1994).

The ankle first goes through plantar flexion at foot strike until foot flat is achieved. At about 40% of the cycle (just prior to opposite foot strike), there is some ankle flexion. Next, plantar flexion occurs at foot off. Finally, there is rapid ankle dorsiflexion during the second knee flexion to help with foot clearance (Rose et al., 1994).

Hill Walking

In a study by Leroux et al., it was found that uphill walking induces increasingly flexed posture of the hip, knee, and ankle during initial contact relative to level of flexion during level walking. This process of adaptation begins in mid-swing with a graded increase in hip flexion and ankle dorsiflexion in addition to a gradual decrease in knee extension (Leroux et al., 1999).

Kuster et al. had three main findings with regard to the kinematics of downhill walking: the ankle joint compensates for the gradient at push off and during swing, the knee joint compensates from early stance through early swing, and the hip joint compensates from early swing through early stance. Difference in peak joint moment and muscle mechanical power was most prominent in the knee joint. A major difference in these measures was also seen in the ankle joint, but only a slight increase in these measures was apparent in the hip joint (Kuster et al., 1994).

Hypotheses

Metabolic Activity

I hypothesize that there will be a significant increase in metabolic activity during tilt walking as compared to activity during level walking because the extra work done by stabilizing muscles requires energy.

Electromyography

I hypothesize that there will be a significant increase in muscle activity for muscles associated with stabilization of the legs during tilt walking as compared to activity during level walking. Particularly, I expect to see an increase in activity of the PL, VL, BF, TFL and ADL because they are primarily associated with joint stabilization.

Kinematics

I hypothesize that there will be a significant change in hip and ankle angles during tilt walking as compared to angles during level walking. I expect the hip angle to change because the tilt will force the hips and everything below it to tilt, but participants will make an effort to maintain their torsos in a vertical position. I expect the ankle angle to change because the tilt will force the ankles to tilt.

However, I hypothesize that there will not be a significant change in knee angles during tilt walking as compared to angles during level walking. I expect the knee angles to stay about the same because the knees will be held in relative position by the hips and ankles.

I hypothesize that there will be a significant increase in step width during tilt walking as compared to step width during level walking. I expect this change because it will improve stability.

On the other hand, I hypothesize that there will not be a significant change in stride time, swing time, stance time, or step length during tilt walking as compared to during level walking. I expect the stride time, swing time, stance time, and step length to stay about the same during tilt walking because I would only expect those factors to vary with upward and downward tilt.

CHAPTER 2: MATERIALS AND METHODS

Participants

Eight college students completed the protocol; of the ten participants, four were male and four were female. All participants signed written consent forms which were in accordance with The Pennsylvania State Human Research Committee guidelines in addition to the Institutional Review Board (IRB) guidelines. Each participant was also asked to provide their birth date, height, and weight prior to starting the experiment. The average age of participants was 21 (for both males and females), the average height was 168.3 cm (174.0 cm for males and 162.6 cm for females), and the average weight was 60.91 kg (66.48 kg for males and 55.34 kg for females).

Set Up

Seventeen reflective markers were positioned on each participant to measure kinematics. The markers were located as follows: lower cervical vertebra (C7), sacral crest, right and left anterior iliac crests, right lateral iliac crest, left lateral thigh, right and left lateral condyles, right lateral shank, right and left lateral malleoli, right and left heels, right and left fifth toes, and right and left great toes. Markers were taped to skin, shirt, or shoes depending on location with medical tape to ensure that they remained in place throughout the experiment.

EMG readings were taken for eight muscles on the left leg. The eight muscles were as follows: Tibialis Anterior (TA), Lateral Gastrocnemius (LG), Soleus (SL), Peroneous Longus (PL), Vastus Lateralis (VL), Biceps Femoris (BF), Adductor Longus

(ADL), Tensor Fascia Latte (TFL). The muscle bellies of these eight muscles were located carefully to ensure accuracy and optimal EMG readings.

Specific guidelines were followed in locating the eight muscle bellies:

1. TA – Along the line from the lower margin of the patella to the lateral malleolous one-third the distance from the patella.
2. LG – Along the line from the fibular head to the heel one-third the distance from the fibular head.
3. SL – Along the line from the fibular head to the heel less than half the distance from the fibular head.
4. PL – On the lateral shank two inches above the lateral malleous.
5. VL – Three to five centimeters from the superior border of the patella.
6. BF – Mid way between the ischial tuberosity and the lateral epicondyle of the tibia.
7. ADL – It was palpated at the superior ramus of the pubus while the participant was standing/conducting an isometric contraction. Upper inner thigh.
8. TFL – It is located two to three centimeters inferior to the iliac crest.

Additionally, a ground position was located on the tibia.

Each muscle belly location as well as the ground location were marked with a permanent marker. Each location was lightly sandpapered to reduce interference and treated with a small amount of rubbing alcohol to clean the surface on which the electrodes would be situated so that readings would be accurate. Two electrodes were placed on the location of each muscle belly angled with the direction of each muscle fiber respectively. However, only one electrode was placed on the ground location. Each self-adhesive electrode was stuck solidly to the skin in order to ensure their integrity during the experiment.

Lead lines were attached to all surface electrodes. They were gathered in an organized manner along the participant's left leg. At this time, the participant was asked to tuck in his/her shirt. Then the lead lines were secured in place using a roll of pre-wrap that was applied around the participant's waist. The EMG battery pack was then wrapped around the participant's waist on top of the pre-wrap. The battery pack was secured firmly, but not so firmly as to cause discomfort for the participant. Each lead wire was inserted in its location on the battery pack and the battery pack was plugged into the computer.

The participant was taken through a series of tests to ensure the proper location of the surface electrodes. To test the TA, the participant was asked to rock back onto his or her heels, and activity was expected to be seen in the TA. To test the LG and SL, the participant was asked to stand on his or her toes, and activity was expected to be seen in the LG and SL. To test the PL, that participant was asked to invert and evert his or her ankle, and activity was expected to be seen in the PL. To test the VL, the participant was asked to stand on his or her right leg and flex the thigh muscles in a fully extended left leg, and activity was expected to be seen in the VL. To test the BF, the participant was asked to resist knee flexion with a hand placed just above the ankle joint, and activity was expected to be seen in the BF. To test the ADL, the participant was asked to press the inside of the left foot in a rightward motion into the leg of a table, and activity was expected to be seen in the ADL. To test the TFL, the participant was asked to push the outside of the left foot in a lateral motion into the leg of a table, and activity was expected to be seen in the TFL. If the functional tests described above demonstrated the correct muscle activity, then the participant was ready to proceed. However, if any functional test demonstrated incorrect muscle activity, then the electrodes at the sites exhibiting incorrect activity needed to be adjusted and retested until shown to be in an accurate position.

Upon appropriate completion of the functional tests, the participant was guided to the treadmill. The participant was fitted with a VO_2 mask to test metabolic activity and wore a nose clip so that he or she could only breathe through the mouth.

Protocol

Prior to the walking trials, each participant completed a seven minute standing trial in order to obtain baseline metabolic information. The participant stood on a level treadmill with arms across the chest breathing only into the metabolic mask. As the participant was not moving, kinematic and EMG data was not gathered during this time.

Upon completion of the standing trial, the participant was ready to begin the walking trials. There were five walking conditions that were administered in a random order to each participant. The five conditions were as follows:

1. Level
2. Six Degree Left Tilt
3. Six Degree Right Tilt
4. Six Degree Up Tilt
5. Six Degree Down Tilt

Each condition was completed at a speed of 1.25 miles per hour and lasted seven minutes. Between conditions the treadmill was stopped and a level was used to adjust the slope. Before stopping or starting the treadmill the participant was asked to use the side rails to hold him or herself up until the treadmill was stopped or started. Participants did not generally remove the metabolic mask or nose clip during this time. However, participants were given a break after completing the standing trial and two of the five walking conditions (the halfway point of the study). During this time they were allowed to take the metabolic mask and nose clip off and get a drink of water. Metabolic data was taken constantly, but the kinematic and EMG data was collected on a trial basis. Each condition consisted of fourteen trials. The trials were administered every thirty seconds and each lasted fifteen seconds.

Statistical Analysis

Data for total stride time, swing time, stance time, step length, ankle step width, toe step width, TA, LG, SL, PL, VL, BF, ADL, and TFL activity were analyzed across conditions using a repeated measures design (ANOVA). Where appropriate, we performed Newman-Keuls post hoc tests and paired Student's t-tests for the metabolic data to analyze the differences between conditions and reported all values as mean $\pm$ standard deviation. Significance, and therefore statistical difference, was defined as $p \leq 0.05$.

CHAPTER 3: RESULTS

Overview

For metabolic activity, significant changes were found for uphill and downhill walking relative to level walking. However, no significant changes were found for tilt walking relative to level walking. For EMG, very few significant changes were found. The significant changes that were found were between activity during uphill walking and level walking. No significant changes were found for activity during downhill walking or tilt walking relative to level walking. For kinematics, again very few significant changes were found. The significant changes that were found were between uphill walking and level walking as well as between downhill walking and level walking. No significant changes were found for gait patterns for tilt walking relative to level walking.

Metabolic Data

The average changes in VO_2 associated with each condition when compared to the standing trial can be seen in Table 1. This data is also visually summarized in Figure 1 below. The average metabolic rate among the participants during the seven-minute standing trial was 4.61 ml kg^{-1} min^{-1}. This value was used as a baseline metabolic value for each participant at rest.

The average changes in respiratory exchange ratio (RER) associated with each condition when compared to the standing trial can also be seen in Table 1. This data is also visually summarized in Figure 2 below. The average RER among participants during the seven-minute standing trial was 0.83. This value was used as a baseline RER value for each participant at rest.

Mean VO_2 (ml/kg/min) and RER					
	L	UP	DN	LF	RT
Participants	VO_2	VO_2	VO_2	VO_2	VO_2
110912	8.18	21.47	5.73	10.15	9.19
111003	6.63	19.45	4.48	7.33	7.38
111010	8.78	20.54	6.99	9.55	8.95
111031	7.55	19.70	5.37	6.43	6.12
111107	8.65	19.98	5.50	8.89	7.91
111205	8.20	20.34	5.84	8.25	8.07
120209	6.98	19.53	4.99	7.89	8.42
120210	6.91	18.07	4.05	5.97	6.70
Mean	7.73	19.89	5.37	8.06	7.84

Table 1. This table presents the mean VO_2 values for each participant in each condition. Mean VO_2 values for all the participants combined are also presented for each condition.

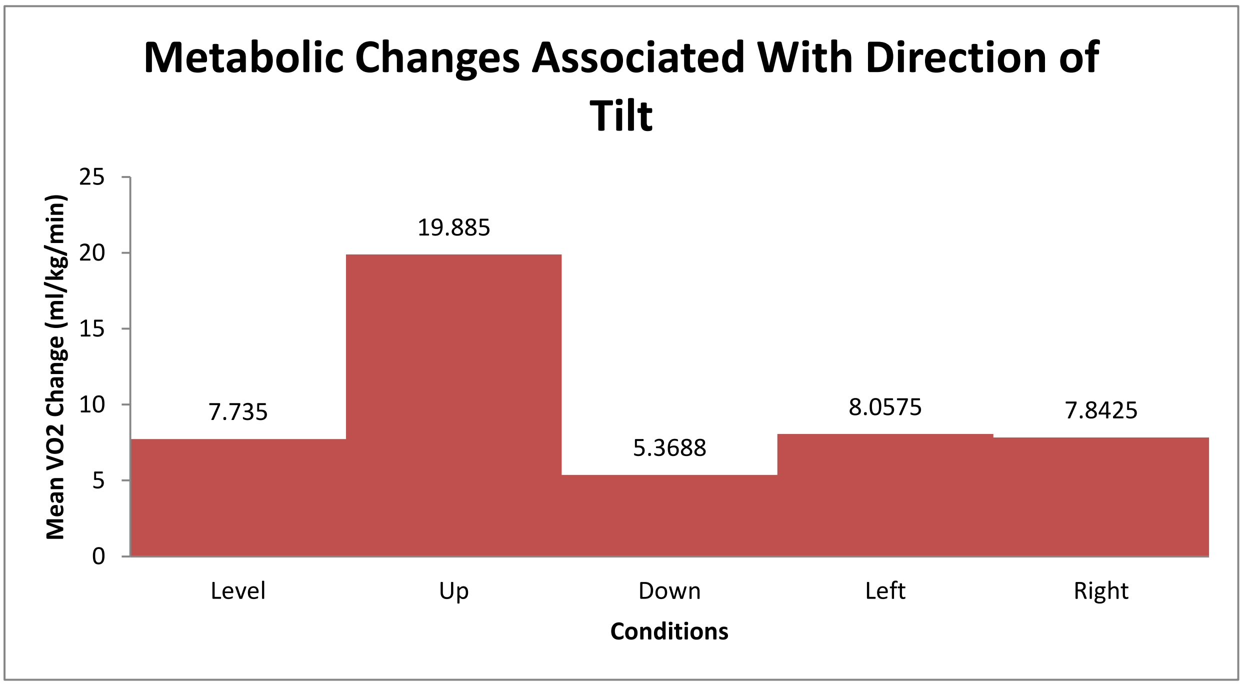

Figure 1. This graph represents the participant means for metabolic cost associated with each condition.

Paired t-tests were run to determine if the results presented above are significant. P-values less than 0.05 were considered significant. Table 2 below presents the p-values for these t-tests for VO_2. Bold values represent significant differences from level.

VO_2			
Up	Down	Left	Right
<0.001	**<0.001**	0.397	0.757

Table 2. This table presents the p-values for each t-test run comparing the VO_2 data for each condition to the VO_2 data for level walking.

These data show that metabolic cost is greater during uphill walking than during level walking. The average metabolic cost during uphill walking at a six degree incline at a speed of 1.25 miles per hour was 19.89 ml kg^{-1} min^{-1} as compared to 7.73 ml kg^{-1} min^{-1} during level walking at the same speed. The increase in metabolic cost during uphill walking from level walking was found to be significant.

These data also show that metabolic cost is less during downhill walking than during level walking. The average metabolic cost during downhill walking at a negative six degree incline at a speed of 1.25 miles per hour was 5.37 ml kg^{-1} min^{-1} as compared to the 7.73 ml kg^{-1} min^{-1} during level walking at the same speed. The decrease in metabolic cost during downhill walking from level walking was also found to be significant.

With regard to tilt walking, both left and right tilt walking demonstrated similar average metabolic costs: 8.06 ml kg^{-1} min^{-1} and 7.84 ml kg^{-1} min^{-1}, respectively. This supports my hypothesis that the metabolic cost of tilt walking is greater than the metabolic cost of level walking; however, the increase in metabolic cost during tilt walking as compared to level walking was shown to be insignificant.

RER values demonstrated a pattern similar to the one found for VO_2 values. RER values for both uphill and downhill walking were found to be significant, whereas RER values for both left and right tilt walking were found to be insignificant. As with VO_2, RER was found to be significantly increased in uphill walking as compared to level walking. Unlike the VO_2 data, RER was also found to be significantly increased in downhill walking as compared to level walking. Coinciding with the VO_2 data for tilt walking, RER was higher during tilt walking than level walking, though this data was not significant.

Electromyography Data

The EMG data showed very few statistically significant differences; three statistically significant differences were found and all three were with regard to activity during uphill walking compared to activity during level walking. Significant differences are marked with a star (*).

<u>TA</u>

Variable	Conditions			
	Up	Down	Left	Right
Initial Stance	145.40*	95.48	81.33	87.40
Mid Swing	142.56	100.53	88.35	99.77

Table 4. This table presents the TA activity for each condition compared to level.

The EMG activity of the TA for each condition is described in Table 4 above. The only significant difference demonstrated by the TA is between uphill walking and level walking during initial stance. Compared to level walking, the activity of the TA during initial stance during uphill walking is 45% higher than its activity during level walking. Although not significant, the TA activity during mid swing during uphill walking is 43% higher than the TA activity during mid swing during level walking. The TA activity during downhill walking is very comparable to its activity during level walking for both initial stance and mid swing. The TA activity during tilt walking is somewhat lower than its activity during level walking; its notable that the TA activity during left tilt walking is less than the TA activity during right tilt walking.

<u>LG</u>

Variable	Conditions			
	Up	Down	Left	Right
Terminal Stance	239.54*	82.15	86.09	95.05

Table 5. This table presents the LG activity for each condition compared to level.

The EMG activity of the LG for each condition is described in Table 5 above. The only significant difference demonstrated by the LG is between uphill walking and level walking during terminal stance. Compared to level walking, the activity of the LG during terminal stance during uphill walking is 140% higher than its activity during level walking. Although not significant, the LG activity during downhill walking is 18% lower than the LG activity during terminal stance during level walking. The LG activity during tilt walking is somewhat lower than its activity during level walking, but its activity is slightly higher than its activity during downhill walking. As with the TA activity, LG activity during left tilt walking is less than the LG activity during right tilt walking.

SL

Variable	Conditions			
	Up	Down	Left	Right
Mid Stance	103.33	123.39	87.44	114.95
Terminal Stance	151.74*	74.24	88.12	95.04

Table 6. This table presents the SL activity for each condition compared to level.

The EMG activity of the SL for each condition is described in Table 6 above. The only significant difference demonstrated by the SL is between uphill walking and level walking during terminal stance. Compared to level walking, the activity of the SL during terminal stance during uphill walking is 52% higher than its activity during level walking. The SL activity during mid stance during uphill walking is not significant; it is only 3% higher than the SL activity during mid stance during level walking. The LG activity during mid stance during downhill walking is 23% higher than its activity during mid stance during level walking, whereas the LG activity during terminal stance during downhill walking is 26% lower than its activity during terminal stance during level walking. The LG activity during left tilt walking is somewhat lower than its activity during level walking; however the LG activity during right tilt walking does not share the same pattern. The LG activity during mid stance during right tilt walking is 15% higher than its activity during mid stance during level walking, while the LG activity during terminal stance during right tilt walking is 5% lower than its activity during terminal stance during level walking.

PL

Variable	Conditions			
	Up	Down	Left	Right
Mid Stance	97.57	125.22	78.68	115.55
Initial Swing	96.85	98.86	78.28	111.71

Table 7. This table presents the PL activity for each condition compared to level.

The EMG activity of the PL for each condition is described in Table 7 above. There are no significant differences with regard to the PL. The activity of the PL during uphill walking is comparable to its activity during level walking; its activity during uphill walking is less than 4% lower than its activity during level walking. Its activity during mid stance during downhill walking is 25% higher than its activity during mid stance during level walking, whereas its activity during initial swing during downhill walking is 1% lower than its activity during initial swing during level walking. The PL activity during left tilt walking is more than 20% lower than its activity during level walking. Differently, its activity during right tilt walking is more than 11% its activity during level walking.

VL

Variable	Conditions			
	Up	Down	Left	Right
Mid Stance	102.67	119.96	90.64	106.58
Mid Swing	105.58	100.60	92.36	99.65

Table 8. This table presents the VL activity for each condition compared to level.

The EMG activity of the VL for each condition is described in Table 8 above. There are no significant differences with regard to the VL. The activity of the VL during uphill walking is comparable (just slightly elevated) to its activity during level walking for both mid stance and mid swing. The activity of the VL during mid swing during downhill walking is also comparable to its activity during mid swing level walking; it is elevated by less than a percent during downhill walking. However, the activity of the VL during mid stance during downhill walking is 20% higher than its activity during mid stance during level walking. Like the LG's activity pattern, the VL's activity pattern during left tilt walking is different from its activity pattern during right tilt walking. During left tilt walking the VL activity is slightly less than its activity during level walking; 9% and 8% lower for mid stance and mid swing respectively. During mid stance during right tilt walking, the VL's activity is 7% higher than its activity during mid stance during level walking, but during mid swing during right tilt walking, the VL's activity is the same as its activity during level walking.

BF

Variable	Conditions			
	Up	Down	Left	Right
Initial Stance	121.16	103.96	86.84	95.34

Table 9. This table presents the BF activity for each condition compared to level.

The EMG activity of the BF for each condition is described in Table 9 above. There are no significant differences with regard to the BF. The activity of the BF during uphill walking is 21% higher than its activity during level walking. The activity of the BF during downhill walking is only 4% higher than its activity during level walking. The activity of the BF during tilt walking is lower than its activity during level walking; its activity is reduced by 13% during left tilt walking and by just 5% during right tilt walking.

ADL

Variable	Conditions			
	Up	Down	Left	Right
Mid Stance	74.83	102.35	63.36	111.51
Mid Swing	79.80	85.68	70.47	100.60

Table 10. This table presents the ADL activity for each condition compared to level.

The EMG activity of the ADL for each condition is described in Table 10 above. There are no significant differences with regard to the ADL. The activity of the ADL is lower during uphill walking than during level walking; its 15% and 20% lower during mid stance and mid swing, respectively. The activity of the ADL is just a little higher during mid stance during downhill walking than during mid stance during level walking (2% higher). Differently, the activity of the ADL during mid swing during downhill walking is 14% lower than during mid swing during level walking. Again, left and right tilt walking exhibit very different patterns. ADL activity during left tilt walking is much lower than its activity during level walking; 37% lower during mid stance and 30% lower during mid swing. ADL activity during mid stance during right tilt walking is 12% higher than during mid stance during level walking, but its activity is less than a percent higher during mid swing during right tilt walking than during mid swing during level walking.

TFL

Variable	Conditions			
	Up	Down	Left	Right
Mid Stance	122.34	104.11	90.15	105.21
Initial Swing	113.06	105.17	92.74	103.63

Table 11. This table presents the TFL activity for each condition compared to level.

The EMG activity of the TFL for each condition is described in Table 11 above. There are no significant differences with regard to the TFL. The activity of the TFL during uphill walking is higher than its activity during level walking by 22% during mid stance and by 13% during initial swing. The activity of the TFL during downhill walking is also higher than its activity during level walking, though only by 4% during mid stance and 5% during initial swing. The TFL's activity during left tilt walking is lower than its activity during level walking; its activity is 10% lower during mid stance and 7% lower during initial swing. Right tilt walking presented a pattern similar to that of downhill walking, The TFL's activity was only 5% higher during mid stance during right tilt walking than during mid stance during level walking and only 4% higher during initial swing during right tilt walking than during initial swing during level walking.

Kinematics Data

The kinematic data describing the gait cycle for each condition is presented in Table 12 below. There are some significant results with regard to uphill and downhill walking as compared to level walking, but there are no significant changes with regard to tilt walking as compared to level walking. Bold values represent significant changes.

Variable	Conditions			
	Up	Down	Left	Right
Total Stride Time (ms)	**103.83**	**94.76**	100.59	100.24
Swing Time (ms)	114.82	89.45	100.33	104.84
Stance Time (ms)	99.731	100.00	100.03	98.67
Step Length	105.22	**91.63**	103.20	97.67
Ankle Step Width (mm)	908.66	290.98	796.09	468.73
Toe Step Width (mm)	424.26	124.55	339.04	270.04

Table 12. This table presents the normalized averages for each gait cycle variable for each condition compared to level.

There is a significant difference between uphill and level walking in total stride time. Total stride time during uphill walking is 3.83% greater than total stride time during level walking. There is also a significant difference between downhill and level walking in total stride time. Total stride time during downhill walking is 5.24% lower than total stride time during level walking. There is no significant difference between either left or right tilt walking and level walking in total stride time. Both left and right tilt walking exhibit a total stride time less than 1% greater than the total stride time during level walking.

There are no statistically significant findings for swing time or stance time.

There is a significant difference between downhill and level walking in step length. Step length during downhill walking is 8.37% shorter than step length during level walking. No other significant differences were found for step length.

There are no statistically significant findings for ankle step width or toe step width.

CHAPTER 4: DISCUSSION

Metabolic Activity

The data collected in this study provide us with three main results:

1. Consistent with previous experiments, uphill walking has a significantly greater metabolic cost than level walking.
2. Also consistent with previous experiments, downhill walking has a significantly lower metabolic cost than level walking.
3. Finally, metabolic cost during tilt walking does not differ significantly from metabolic cost during level walking.

The results obtained in this study are consistent with the literature. Here, it is shown that uphill walking has a significantly greater metabolic cost than level walking. Minetti et al. achieved this same result (Minetti, 2001). It is also shown that downhill walking has a significantly lower metabolic cost than level walking. Minetti et al. achieved this same result as well (Minetti, 2001). This study only measured metabolic cost at one downhill incline (-6 degrees), so not enough data were gathered to show that metabolic cost during downhill walking eventually increases as the downhill incline becomes more severe; a finding that is quite prevalent in the literature.

As there is a great deal of research that has been done on uphill and downhill walking, the real purpose of this study is to focus on tilt walking and how it compares to and differ from level walking. I hypothesized that tilt walking would require greater metabolic activity than level walking. Although this is shown to be true, tilt walking only requires slightly more metabolic activity than level walking, and the results are not statistically significant. Saltin provides a reasonable explanation for these findings. He determined that 52% of metabolic cost is used for propulsion, 40% is used for braking, and 6% is used for stabilization (Saltin, 1973). Since tilt walking primarily increases the need for stabilization but has little to no effect on the need for propulsion or braking, it is affecting a factor that requires little metabolic activity to begin with. As such, it makes sense that there is a slight increase in metabolic activity during tilt walking as compared to level walking, but it also makes sense that this increase in metabolic activity is not statistically significant. This also explains why uphill and downhill walking have significantly different metabolic activities; uphill walking requires more propulsion, which is a huge portion of the metabolic cost, and downhill walking requires less propulsion.

Electromyography

The EMG data collected for this study included data for eight different lower body muscles: TA, LG, SL, RF, VL, BF, ADL, and TFL. Each of these muscles functions in a specific manner toward the overall goal of a fluid gait. The EMG data presented in this study can help us understand how each muscle adapts to each of the different conditions.

For the TA, the only significant difference demonstrated is between uphill and level walking during initial stance. Although not significant, there was also a large difference between uphill and level walking during mid swing. Its activity during downhill walking is comparable to its activity during level walking. Its activity during tilt walking is slightly lower than its activity during level walking. The literature suggests that previous findings for the activity of the TA during different conditions are inconsistent across studies; the activity is too variable to be tested accurately (Lay et al., 2007). Therefore, it is difficult to judge the quality of the TA results in this study. The activity results for the tilt walking did coincide with my original hypotheses though. The TA acts during swing, so it makes sense that its activity would not significantly differ with conditions that require more adaptation with regard to stance and balance (Winter, 1991).

The LG also demonstrated just one significant difference, and, again, it is between uphill and level walking; the LG showed higher activity during uphill walking. This makes sense because the LG is active during push-off, which needs to be more powerful when walking uphill (Winter, 1991). Similarly, downhill walking would require a less powerful push-off, which corresponds with the findings of this study, which show that the LG is less active during downhill walking. As the LG is associated with push-off, I hypothesized that its activity would not differ significantly during tilted walking, and this expectation was confirmed by the results of this study.

Like the TA and LG, the SL has just the one significant difference between uphill and level walking during terminal stance. This is logical because the SL is associated with the production of an explosive push-off, and a more explosive push-off would be necessary during uphill walking as compared to level walking (Winter, 1991). This data also is an agreement with the findings of Lay et al. (Lay et al., 2007). The SL does not exhibit any other statistically significant effects, though it would not have been surprising if it had shown significantly decreased activity during downhill walking given its function. Its activity during tilt walking does not significantly differ from its activity during level walking as was hypothesized. This makes sense because tilt walking does not create a demand for a more or less explosive push-off like for uphill and downhill walking, respectively.

The PL exhibited no significant effects. This is surprising because the PL is important for push-off and stabilization (Winter, 1991). This would lead me to believe that the PL activity could be significantly different for all the conditions. Maybe this was not the case because each isolated condition was not enough to alter the PL's activity in a significant way; maybe a condition in which the plane is tilted both up or down and left or right would yield significant effects.

No significant effects were shown for the VL. As the VL primarily functions in weight acceptance, it makes sense that its activity would not differ significantly during uphill and downhill walking (Winter, 1991). However, I hypothesized that its activity would increase significantly during tilt walking as compared to its activity during level walking because of the VL's role in stabilization, which should require more effort to maintain during tilt walking. The results did not show this to be true. The results demonstrate that the VL's activity does not differ significantly during tilt walking as compared to during level walking. This is likely attributed to the fact that only 6% of metabolic cost is used for stabilization and metabolic activity and muscle activity are associated (Saltin, 1973). Thus, it is logical to say that only 6% of muscle activity is used for stabilization making it very unlikely that an activity like tilt walking, which requires more effort to maintain stability, would require significantly more muscle activity.

The BF also has no statistically significant effects. Like the VL, it primarily functions in weight acceptance, so it makes sense that its activity would not differ significantly during uphill and downhill walking (Winter, 1991). This disagrees with the research conducted by Lay et al., which found that BF activity significantly increases during uphill walking as compared to during level walking (Lay et al., 2007). With regard to this, it is worth noting that although the results do not show a significant increase in BF activity during uphill walking, the BF activity during uphill walking is 21% higher than its activity during level walking. I hypothesized that there would be a significant increase in BF activity during tilt walking relative to during level walking, but this is not indicated by the results. As with the VL, this can be attributed to the limited amount of resources dedicated to maintaining stability (Saltin, 1973).

The ADL and TFL also show no statistically significant results. They are primary muscles for stabilization, so, like with the previous muscles, it makes sense that their activity would not differ significantly during uphill and downhill walking (Winter, 1991). My hypothesis was that there would be a significant increase in activity for both of these muscles during tilt walking relative to during level walking, but this, too, is not shown by the results, and, again, this can be attributed to the limited amount of resources dedicated to maintaining stability (Saltin, 1973).

Kinematics

I studied six variables within the gait cycle: total stride time, swing time, stance time, step length, ankle step width, and toe step width. There are many factors that can affect these variables. Some of these factors are velocity (Nilsson, 1985), grade (Davies, 1974), footwear (Clarke, 1983), anthropometric dimensions, muscle fiber composition (Heikki, 1978), among others.

For total stride time, a significant difference was found between uphill walking and level walking as well as between downhill walking and level walking. Total stride time was greater in uphill walking than in level walking and lower in downhill walking than in level walking. A significant difference was also found between downhill walking and level walking for step length. The step length was found to be shorter in downhill walking. No other significant differences were found for any of the variables in comparing uphill walking with level walking and downhill walking with level walking.

There were absolutely no significant differences in any variable in comparing right and left tilt walking with level walking. My hypotheses were mostly correct. I initially hypothesized that no variable would exhibit a significant difference in the comparison of tilt walking with level walking with the exception of the step width; I had anticipated that the step width would be greater during tilt walking than during level walking, but this was not the case. I suppose it is possible that the tilt was not extreme enough to yield such a result. Maybe if the tilt had been greater than six degrees we would have seen an increase in step width.

Limitations

Steps were taken to ensure the quality of this study such as randomized trials, having an equal number of males and females, among others, but, like any other study, there were some limitations.

First of all, there were relatively few participants. This study only collected data for eight participants, which is a very narrow scope. Having more participants would enhance the power of the statistical tests performed.

Secondly, almost all the participants were 21 years of age. Six out of eight were 21, one was 20, and one was 22. The participants are all within a very narrow age range, which limits the generalizability of the data to other age groups.

Finally, metabolic data is sensitive to the environment to which an individual is exposed (Hermansen, 1973). This meant that I had to approach the metabolic activity analysis with caution. In order to avoid skewing the metabolic activity of adjacent trials, the first three minutes of each seven minute trial was not considered. This left four minutes of metabolic data for each condition, which was plenty, but the problem is that it is possible that three minutes was enough for a person to adapt his or her metabolic activity to the new condition, in which case the adaptation of the metabolic data would be missed in the analysis, and fewer significant differences would be seen than should have been seen.

Future Research

As this study explores a topic that has been explored very little, there is a great need for future research on tilt walking. Future research could focus on any number of related topics, but simply continuing to explore tilt walking and how it affects metabolic activity, electromyography, and kinematics would be quite useful.

Studies could certainly be designed to address particular limitations of this study. For example, repeating this study with more participants and a more varied group of participants would increase the reliability and generalizability of the results. Secondly, it would certainly be worth it to study metabolic activity at the beginning of each condition. This could provide us with clues as to whether people adapt their metabolic activity to a given condition or if metabolic activity really does not differ significantly during tilt walking relative to level walking. Furthermore, studies could be conducted with higher angle tilts to see how metabolic activity, muscle activity, and kinematics vary with increased angle tilts.

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ACADEMIC VITA

Hossam Abdou

Education

Pennsylvania State University
University Park
Schreyer Honors College
Graduation 2012
B.S. in Biology (Vertebrate Physiology Option)
B.S. in Psychology (Neuropsychology Option)
Dean's List FA08, SP09, FA09, SP10, FA10, SP11, and FA12

Employment Experience

Lab Assistant at Academic Urology Pathology Lab
June 2011-August 2011

- Prepared slides for the pathologist using immunohistochemistry staining techniques
- Learned about histology, how to interpret slides

Teaching Assistant in the Pennsylvania State University Biology Department
August 2010-May 2011

- Instructed students in the lab component of a cell biology course and an animal physiology course
- Taught techniques including how to use microscopes, micropipettes, and spectrophotometers; also taught how to isolate DNA

Researcher in the NSF-REU Program at Carnegie Mellon University
May 2010-July 2010

- Conducted molecular biology research and learned various molecular biology lab techniques
- Acquired extensive experience cloning
- Acquired extensive experience imaging (imaged the cell death process)
- Produced a PowerPoint presentation and a poster presentation on my research concerning the imaging of cell death processes

Researcher at Temple University
May 2009-August 2009

- Conducted bio-organic chemistry research with the aid of a postdoc
- Gained experience in the research lab setting
- Collaborated with undergraduate students, graduate students, and professors in conducting the project

Interests and Activities

Shadowed a physician at the Children's Hospital of Philadelphia

June 2009-August 2009

- Shadowed pediatric cardiovascular specialist, Dr. Seliem, at the Children's Hospital of Philadelphia

Community Service

September 2007~ Present

- Penn School of Medicine
  - Volunteered in an anesthesiology lab for about 15 hours/week over summer 2011 helping conduct experiments such as western blot as well as helping train new researchers
- Chester County Hospital
  - Volunteered in the Emergency Room and the Radiology Department helping with patient care for 100 hours over summer 2009
- Annual Bike/Coat Drive run by Unionville High School
  - Helped in the process of fixing donated bikes and with the distribution of donated coats and bikes to those less fortunate
- Tutoring
  - Tutored children between third and fifth grade
- SCCSA Soccer
  - Coached an Under-7 Soccer team

THON Volunteering (Donor Relations and Communications Committees)

September 2009~February 2012

- Worked collaboratively to raise millions of dollars for cancer research