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Energy Expenditure and Stability During Self-Paced Walking on Different Slopes

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ENERGY EXPENDITURE AND STABILITY DURING SELF-PACED WALKING ON DIFFERENT SLOPES

by

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B.S. University of Central Florida, 2016

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Major Professor: Helen J. Huang

ABSTRACT

Metabolic power and cost of transport (COT) are common quantifiers for effort when performing tasks including walking and running. Most studies focus on using a range of normal walking speeds over level ground or varied slopes. However, these studies use fixed-speed conditions. Fatigue, stability, metabolic expenditure, heart rate, and many other factors contribute to normal walking speed varying over time. This study aimed to show that allowing a subject to walk with a self-paced speed should correlate to a minimum COT at a given slope. This study also aimed to determine if a preferred slope exists based on minimizing metabolic expenditure or maximizing stability. In this study, subjects walked at four different speed conditions including three fixed speeds (0.75 m/s, 1.0 m/s, 1.25 m/s) and their self-paced speed at five different slopes (-6°, -3°, 0°, 3°, 6°) while metabolic energy expenditure and motion were recorded. The minimum COT occurred at a 3° decline. At this slope, some subjects preferred to walk at a faster speed compared to level ground, whereas other subjects walked with a slower speed compared to level ground. Thus, there was a greater range of self-paced speeds, from 0.745 m/s-2.045 m/s. In comparison, at a 6° incline, the range of self-paced speeds was much smaller, from 0.767 m/s-1.434 m/s. The variance among self-paced speeds and slope conditions between subjects suggests that COT, alone, does not explain walking decisions; stability might play a greater role than initially believed. These results provide greater insight into why humans choose to walk at a certain speed over a range of slopes and terrains.

This work is dedicated to my amazing husband, Luke,

my parents, John and Selena,

my in-laws, Mark and Margaret,

and friend, Kirsten,

for their love and support.

Thank you for always believing in me

and for the help along the way.

I wouldn’t have been able to accomplish this without you all.

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CHAPTER 1: INTRODUCTION

Background

From walking to running, human locomotion is unique and changes as we age. We are constantly moving, and very little thought goes into the process of putting one foot in front of the other. We only think about walking when our muscles start to get sore, we lose our balance, or we need to catch our breath. The best way to quantify the factors involved in locomotion and the decisions that people make when walking is to measure it in a controlled, yet natural setting.

Metabolic systems and respirometers are commonly used in the medical and research fields to quantify exertion in the form of metabolic cost of transport (COT). Portable systems allow for researchers to study subjects during normal locomotion or when completing a variety of tasks. Metabolic cost is frequently used to study fixed walking speeds on a treadmill on a variety of slopes. However, most studies focus on either level ground with varied speeds, faster speeds, or more extreme slopes [1, 3, 6, 8, 12, 17, 19, 21, 32, 34]. For this research, we are interested in a slower range of speeds closer to the preferred walking speed of older adults and slopes near what people would traverse on a regular basis [17]. Currently, there is no collective set of metabolic data for self-paced walking on different slopes. Most papers will report "self-selected" speed which is an average over-ground speed measured prior to recording data on the treadmill [16, 29, 31, 33]. However, the "self-selected" speed is still a fixed speed. Most people vary their speed depending on their environment and bio-feedback and will not walk at one set speed for a long period of time. As technology advances, researchers can collect more data and test more conditions in a controlled setting than before. Now, we can record the locomotion data we need in the lab that cannot be recorded outdoors including motion capture over long periods of time and varying slopes and speeds, including self-paced.

Systemic coordination of the brain's motor control area, motor neurons, muscles, and more help people walk over varying landscapes and with different speeds. Walking involves many factors including speed, step frequency, step width, step length, stability, and energy cost. These factors are accounted for with every step a person takes. People can adjust how they walk instantaneously to account for the energy being used [3]. A metabolic landscape can be created to depict the factors that people use to decide how they are going to walk and shows the energy expenditure for each decision. The landscape can be adapted to include terrain or environmental factors and predict the speed and preferred slope a person will choose when walking to minimize metabolic cost.

Self-Paced Walking

People do not naturally walk at a constant speed; instead, they fluctuate speed depending on environmental factors, energy expenditure, and mechanical factors. Since metabolic rate provides slow feedback, people are constantly decelerating or accelerating, side-stepping, fluctuating step frequency, varying step length, and changing step width depending on visual cues of their environment and predicted speed to choose a preferred speed [26]. Constraining a person to walk at a fixed speed, even if it is their preferred over ground speed, limits our understanding and ability to study natural human locomotion. When people walk outside, many visual cues provide insight into their environment and speed, but a treadmill does not provide the same visual feedback and changing environment. However, self-paced speeds are comparable between over ground walking and treadmill walking after the first 50 meters without visual feedback [29].

Having the ability to test people using a self-paced treadmill allows people to walk with more natural speed fluctuations, even if the visual flow is different compared to outdoors. With the treadmill being self-paced, researchers can test inclines and declines and measure motion capture and reaction forces which cannot easily be done over ground [36]. Many groups can test slopes or self-paced but not both [1, 3, 6, 8, 12, 17, 19, 21, 32, 34]. Some researchers in the past were able to investigate spontaneous, self-paced walking speeds on different slopes using a range finder and treadmill connected to a computer. They showed that self-paced walking speed and step frequency decrease as slope increases [22]. However, the delay was nearly 0.5 seconds. With modern technology, new instrumented treadmills are now able to match a subject's speed by using motion capture synchronization. Overall, gait patterns measured with instrumented treadmills which allow for self-paced walking and the gait patterns measured with fixed-speed treadmills were not significantly different [36]. This shows that instrumented treadmills are a good alternative to fixed-speed treadmills and will allow measurements of the natural gait fluctuations normally seen in over ground walking.

Metabolic Power and Cost of Transport

Respiration involves the exchange of O_2 with the waste product CO_2 by inspiration and expiration. The respiratory exchange ratio (RER) is the ratio of CO_2 produced to O_2 consumed as shown in Equation 1 [30] and is equivalent to the respiratory quotient (RQ).

$$\boldsymbol{RER = \frac{CO_2\ produced}{O_2\ consumed}} \tag{1}$$

RER, or RQ, typically falls between 0.7 and 1.0. O_2 is consumed by the body using the metabolism to create sources of energy and heat from carbohydrates, fats, and proteins. At rest, most energy comes from fats and carbohydrates. Protein is only consumed after prolonged exercise. As exercise duration increases, the body shifts from burning fat to oxidizing carbohydrates. When the body burns fat, RER is near 0.7; as the body starts to use more carbohydrates, RER approaches 1.0. RER can become greater than 1.0 when sodium bicarbonate can no longer buffer lactate acid and the exercise surpasses the lactate threshold. With all things considered, RER is a good indicator of the metabolic process in the body and provides insight into energy consumption. To calculate RER, CO_2 and O_2 must be measured using a respirometry system, like the one shown in Figure 1. The metabolic system contains a CO_2 sensor which uses infrared spectroscopy and an O_2 sensor which uses micro fuel cell technology.

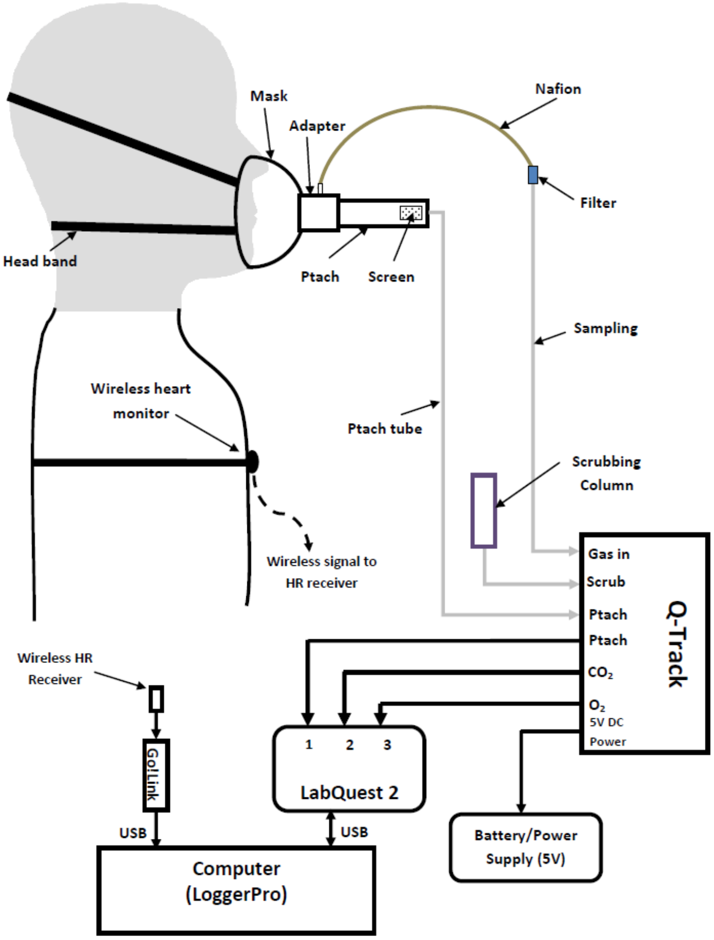


Figure 1: Respirometry system set up [30]

Using the measured O_2%, CO_2% and flow rates, the volumetric flow rate of CO_2 ($\dot{V}CO_2$) and O_2 ($\dot{V}O_2$) can be determined. From this, metabolic power can be calculated using Brockway's equation, shown in Equation 2 [5].

$$\boldsymbol{P_{met,gross} = 16.58\frac{W*s}{ml\,O_2} * \bar{\dot{V}}_{O_2} + 4.51\frac{W*s}{ml\,CO_2} * \bar{\dot{V}}_{CO_2}} \qquad (2)$$

The resting metabolic power is subtracted from Equation 2 to find the net metabolic power, or the power needed to perform a task. COT is found using Equation 3, where $P_{met,\,net}$ is net metabolic power and v is velocity (m/s).

$$\boldsymbol{COT = \frac{P_{met,net}}{v}} \qquad (3)$$

Both metabolic power and COT are useful for comparing effort for different walking conditions and have been well established as standard metabolic measurements [1, 3, 6, 8, 12, 17, 19, 21, 32, 34].

Researchers have constantly explored the idea of locomotion optimization and discussed whether evolutionary effects like body shape and neural control or life experience of learning every aspect of walking firsthand play a greater role in people finding their optimal gait. Now, biomedical engineers are designing assistive robotic devices including exoskeletons and powered prosthetics that can learn and adapt to find a person's optimal gait using algorithms based on metabolic expenditure over various terrains and conditions [10, 32]. Metabolic power and COT are used to determine the effectiveness and quality of assistive devices and help finetune and improve them. It is also used to compare different walking and running speeds, slopes, reaching activities, and many other conditions [1, 3, 6, 8, 12, 17, 19, 21, 32, 34]. When walking on different slopes, COT increases on inclined and declined conditions for animals, including ants [20]. Plots of COT versus speed show a consistent U-shape which can shift up, down, left, or right depending on the conditions. Figure 2 shows COT plotted against preferred walking speed for a predictive model compared to experimental values in a level walking experiment (DS is double support, SS is single support) [31]. These plots help show that there is a minimum COT associated with walking at preferred speed and make it easier to compare experimental conditions.

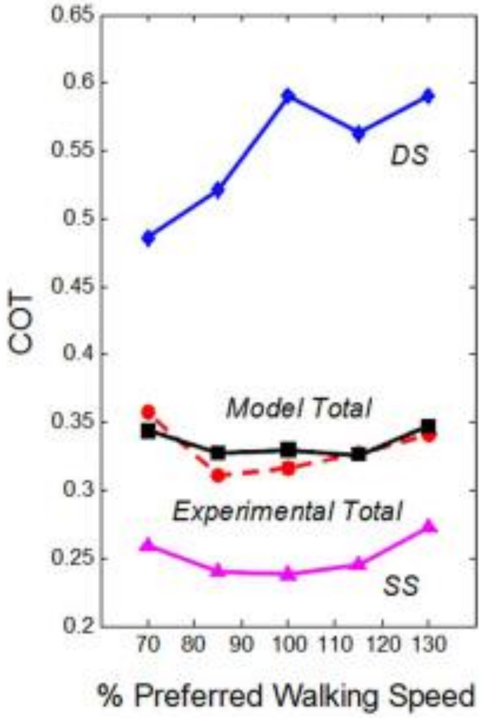


Figure 2: COT as a function of preferred walking speed. Minimum COT is associated with walking at a preferred speed for a given condition. [31]

While metabolic cost is commonly used and easy to measure, it has a slow response rate to changes when compared to other measures of effort like muscle activity, and it is restricted to steady-state measurements. Generally, it takes a person three minutes for their metabolic cost to plateau and reach steady state before measurements are meaningful [10]. From this, steady-state cost mapping can be accurately created using a single parameter. Since the response of metabolic cost is slow, people are inclined to use visual feedback of their surroundings to alter their speed to match and select a preferred speed [26]. Researchers are currently investigating strategies to estimate the metabolic cost without the need to reach steady state. Instantaneous energetic cost mapping is a new method based on multiple parameters to allow for instant estimates of cost without having to wait for steady state [10]. Other studies have shown that there is a measurable relationship between a person's height, weight and walking speed to the energy cost of locomotion [39]. Figure 3 shows the positive correlation between metabolic energy expenditure (MEE) and mass, height, maximum $\dot{V}O_2$, and maximum knee torque [31].

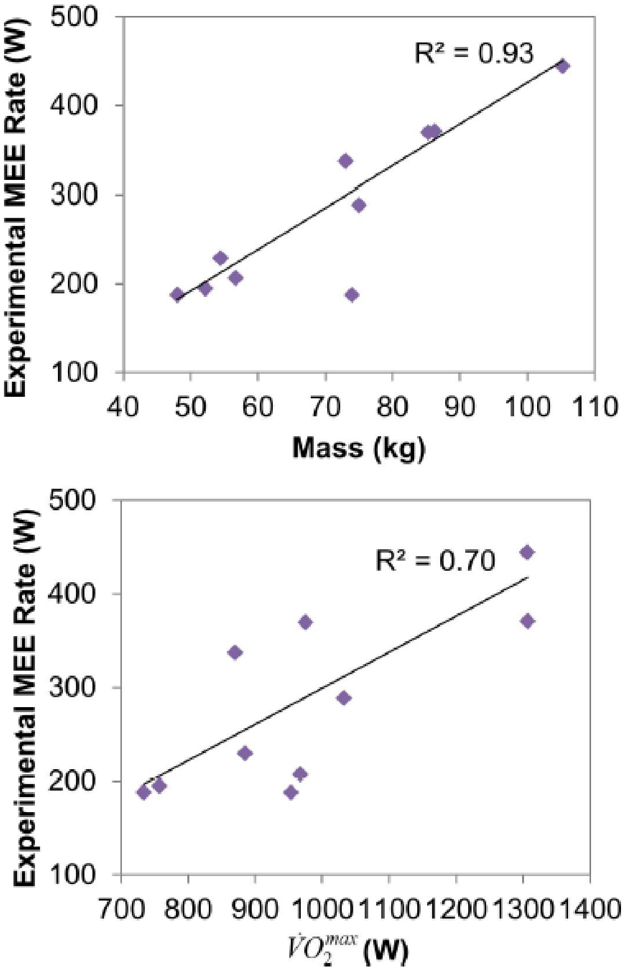


Figure 3: A positive correlation between metabolic energy expenditure (MEE) exists between mass, height, maximum $\dot{V}O_2$, and maximum knee torque [31].

A model to predict metabolic rate was created using resting metabolic rate, minimum walking metabolic rate, and the speed-dependent rate. The model accurately predicted the metabolic rates within 10% of the actual value. When walking up inclines, a linear regression model for metabolic cost can accurately be predicted from electromyography (EMG) measurements from the different leg muscle groups, excluding gluteus maximus [35]. The soleus and vastus medialis, alone, accounted for the majority of metabolic cost variance during incline walking. Similarly, another subject-specific model exists to estimate COT using specific heat and work [31].

Interestingly, when discussing the inverted pendulum model of walking, the swing phase of walking contributes little to the overall metabolic cost. The primary source of energy use is from the stance phase of walking [13]. This is due to the muscles in the legs performing work to support the weight of the body. Even when loads increase, the energy used during the swing phase does not change. Many studies underestimate the metabolic expenditure of the leg muscles because they neglect the double support phase of walking, and they cannot take the isometric muscle contractions needed for stability into account. Another study compared metabolic cost of fixed-speed walking to oscillating-speed walking [33]. Oscillating-speed walking was performed by walking slower and faster than the fixed speed on a treadmill. This study showed that walking at a fixed speed used less energy compared to oscillating speeds. This means that the metabolic cost of starting and stopping, or changing accelerations, accounts for a greater percent of metabolic expenditure of walking. This increased metabolic cost is likely due to the changing kinetic energy needs and greater demand on the muscles to alter the speeds. However, people can continuously optimize their walking patterns to minimize energy expense, even when the savings are small. When looking at step frequency, the net metabolic power is minimized at the preferred step frequency. When subjected to resistance that affects the ability to walk at the preferred frequency, subjects continue using their preferred step frequency until they adapt to either a slower or faster frequency corresponding to the new metabolic minimum [34]. Similarly, in downhill walking, if subjects relaxed their muscles and let gravity do more work, metabolic cost decreased to a new minimum at the expense of stability or increased stride variability [18].

Metabolic COT, alone, does not fully explain why people walk at certain self-selected speeds [24, 25, 33]. Time to complete a trial or total distance traveled might play a larger role in the decision. Overall, subjects tended to minimize time or distance rather than energy when given the ability to select speed [37]. Downhill walking would allow people to minimize metabolic cost compared to level ground by using gravity advantageously, but it would also cause a decrease in stability. This suggests that people would rather choose a walking gait that does not minimize metabolic cost, but, instead, allows them to be more stable [18].

Stability

There are many ways to quantify stability. Stability is the ability to recover from perturbations during each step and actively adapt gait. Variability measures the changes in different parameters and provides insight into the level of stability by relating the data to the walking cycle and averaging the discrete measurements over the entire trial [7]. Some common measures of stability are step width, step length variability, step width variability, margin of stability, and stride frequency variability. Step length is the distance between each foot in the anterior-posterior direction, while step width is the distance between each foot in the medio-lateral direction. A stride consists of 2 steps, and stride frequency is the rate at which a stride is taken. Margin of stability (MOS) is a derived measurement from center of mass (COM) and center of pressure (COP). One study reported that COP variability is minimized on level ground and increases with changing slope [9]. MOS is useful when conducting trials intended to measure stability and instability when subjected to perturbations, but this requires the use of a force plate.

Medio-lateral MOS has a positive correlation to stride frequency, whereas backwards MOS is related to increased speed or decreased step length [14]. Since this experiment is not using perturbations, step length variability, step width variability, and stride frequency variability will be used to quantify stability.

Walking is historically modeled as an inverted pendulum which uses passive mechanics like gravity and converts it to kinetic energy to swing the legs forward. Walking can be broken into different stages: single support, where one foot is on the ground and the other swings, and double support, when both feet are on the ground. To initiate a step, center of mass moves in front of the center of pressure which creates a pivot point and allows the leg to swing forward [27]. This, combined with altering sagittal ankle moment during single support phase, allows people to change their speed on demand. The differences in kinematics of the lower body for self-paced speed compared to fixed speed are negligible. As people take steps and alternate between stance and swing for each leg, they rely on passive and active controls to maintain balance and stability. Step width and step length are common calculations performed to compare trial-based variability of stability. When people walk, they are more stable in the anterior-posterior directions and unstable in the medio-lateral directions [25]. This instability requires active control of the muscles to maintain balance. Another active control measurement used for stability is step variability or center of pressure (COP) variance. This measurement can show how often someone shifts their weight or lands differently when walking.

When people walk at their preferred step width and length over level ground it generally corresponds to their metabolic COT minimum [37]. However, changing slopes and speeds makes walking at preferred step width and length more difficult. People tend to choose a step length greater than that which minimizes energy expenditure [2]. Similarly, when walking downhill, people choose to maximize stability rather than minimize metabolic cost [18]. This suggests that stability, joint biomechanics, and overall comfort might play a greater role in choosing step width and length over energy expenditure. When subjected to visual perturbations and distractions, step variability and metabolic cost both increase to maintain stability [24, 25]. This implies that there is a coupled relationship between stability, step variability, and metabolic cost. Perturbations in the medio-lateral direction produced the greatest increase in metabolic cost and step width, while step length did not significantly change. Older adults and those with gait abnormalities walk with increased step variability, particularly step width, and have a higher metabolic expenditure rate. However, this higher rate is due to factors other than step variability for older adults [28]. For step length, people prioritize taking symmetric steps over step frequency and time between steps [11]. Over time, people walking on a split-belt treadmill traveling at different speeds will adapt and regain step symmetry. Metabolic cost of symmetric steps is lower compared to asymmetric steps.

When it comes to stride rate or step frequency, preferred step frequency consistently corresponds to the metabolic minimum and maximum stability when people are subjected to different fixed-speed conditions [15, 16, 38, 40]. The preferred step frequency is chosen due to systemic self-optimization and the resonance properties of the oscillating limbs. As step frequency increases above the preferred rate, metabolic cost increases due to the increased mechanical work the limbs must perform. Whereas, when step frequency decreases below the preferred rate, metabolic cost increases due to a decreased mechanical efficiency of the limbs. People can learn to adapt to different step frequencies than what they prefer, but only if there is a metabolic benefit to creating the change [23, 34]. However, people will still walk at their preferred step frequency even when it does not equate to a metabolic minimum, and they must learn to optimize their gait through experimental methods and exploring different options. Even increased loading does not cause a significant change in preferred step frequency [13]. A person's preferred step frequency is chosen based on the fixed speed they are subjected to [4]. When a person can choose their speed or the speed varies, there is more variability with step frequency due to the fluctuations in speed.

Hypothesis

The purpose of this study was to quantify the metabolic expenditure needed to walk at a range of slower fixed speeds and self-selected speed over a range of slopes. We aimed to determine which speeds people preferred on a given slope and how it compared to fixed speeds. We hypothesized that the self-selected speed would correspond to the metabolic minimum in most cases. For those who did not choose a speed that minimized metabolic cost, we aimed to show that stability contributed to that decision. Also, we aimed to find which slope minimized metabolic cost, regardless of speed, and predict which factors contributed more to this slope.

CHAPTER 2: METHODOLOGY

Experimental Procedure

Six healthy, young adult males and four healthy, young adult females (23.40±1.56 years; 68.81±13.94 kg) successfully completed the experiment. Individual subject characteristics are shown in Table 1 below. To take part in the study, subjects had to be between 18-35 years old; had to have no neurological, musculoskeletal, or other problems that affected movement control; had to have no cardiopulmonary or other problems that affected breathing; had to have no recent history of falls; and had to be able to walk for at least 1 hour. Subjects were instructed to fast for at least three hours before the collections.

Table 1: Individual subject characteristics

Subject #	Age (years)	Mass (kg)	Sex
1	26	95.254	M
2	25	70.306	F
3	25	58.513	F
4	23	83.914	M
5	21	78.017	M
6	23	50.802	F
7	24	61.235	M
8	23	52.163	M
9	21	59.874	F
10	23	78.017	M

The experimental protocol was approved by the Institutional Review Board (IRB) of the University of Central Florida. Subjects completed a total of 20 trials using a combination of four speeds (0.75 m/s, 1.0 m/s, 1.25 m/s, self-paced) and five slopes (-6°, -3°, 0°, 3°, 6°) on a force plate treadmill (Motek M-Gait, Amsterdam, Netherlands) on two separate days around the same time of day. The trial order for each subject was randomized to reduce the effects of fatigue on the data. Subjects wore a face mask attached to the metabolic system (Qubit Systems Inc., Kingston, ON, Canada) which recorded $\dot{V}CO_2$, $\dot{V}O_2$, RER, and breath start and stop times. A 22-camera Optitrack motion capture system and Motive software (NaturalPoint, Inc. Corvallis, OR, USA) was used to collect kinematic data from 16 lower body markers using the Optitrack conventional marker set. The experiment set up is shown in Figure 4. For each collection, the resting metabolic rate was recorded from quietly standing on the treadmill for five minutes followed by 10 six-minute conditions with breaks in between. During each condition, RER was monitored. Only subjects in steady state with RER<1 and $\dot{V}O_2$ leveling were included. Before each collection began, the treadmill, motion capture system, and metabolic system were calibrated according to the manufacturers specifications.

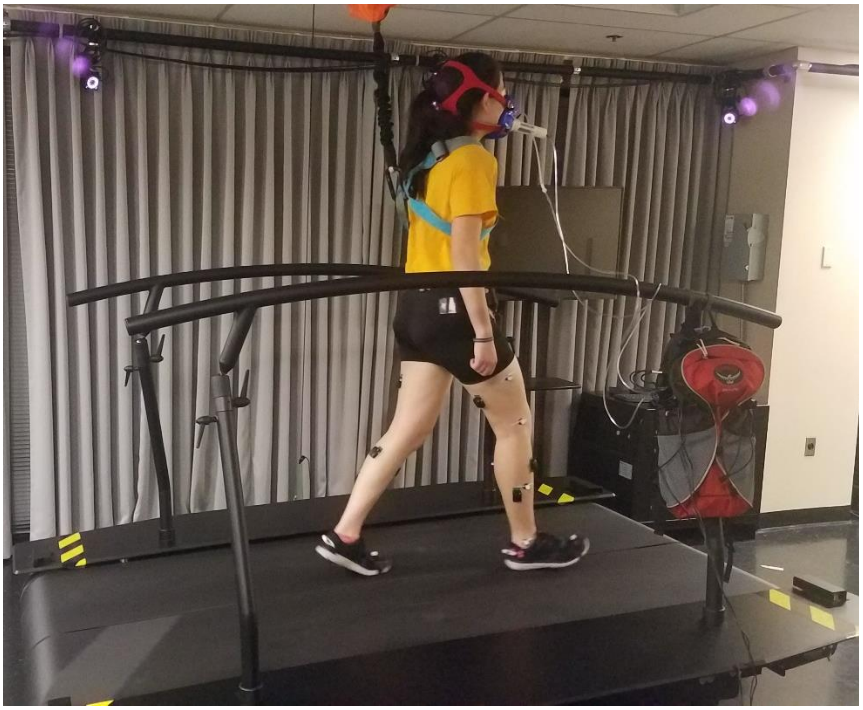


Figure 4: Experiment set up with subject walking on treadmill while metabolic and motion capture data is collected

Data Analysis

The metabolic data was processed with a custom Logger Pro program (Vernier, Beaverton, OR, USA) to determine the volumetric flow rate of CO_2 ($\dot{V}CO_2$) and O_2 ($\dot{V}O_2$). More analysis and calculations were performed using the Logger Pro results in MATLAB (MathWorks, Inc., Natick, MA, USA). The motion capture and treadmill data were processed using a custom MATLAB code. Normalized net metabolic power was calculated for each subject by subtracting the resting metabolic rate from Brockway's equation, Equation 2, and dividing by their mass. Minutes three to five of the data were used for each subject as they were considered to be in steady state. This data was then fit with a quadratic equation as a function of slope. Equation 4 shows the general form of the quadratic fit equation used for net metabolic power as a function of slope.

$$\boldsymbol{P_v(\theta) = a * \theta^2 + b * \theta + c} \tag{4}$$

This process was repeated to create a fit for net metabolic power as a function of speed. The net metabolic power was also plotted as a function of speed for each subject and fit with a quadratic equation like Equation 5.

$$\boldsymbol{P_\theta(v) = a * v^2 + b * v + c} \tag{5}$$

From this, COT for each individual subject was determined by dividing the net metabolic power fit equations by the mean velocity during minutes three to five.

The fit coefficients for the individual subjects were averaged to get overall group fit equations for both net metabolic power as a function of speed and slope. This process was repeated to find a group fit for COT as a function of both speed and slope. These group fit equations were compared to the fit equations obtained by first finding the average net metabolic power for each speed and slope condition. Plots for net metabolic power and COT versus slope and speed were created for each individual and the group.

A landscape was created using the fit equations for COT as a function of both speed and slope to compare the fixed and self-paced speed conditions. The landscape gives insight into potential locomotion decisions made due to speed, slope, and COT.

The average step width, step length, and stride time were determined for each subject and condition as related to the walking cycle using the motion capture system. Each step cycle began at right heel strike followed by left toe off, left heel strike, and right toe off. The slope of the treadmill was used to accurately find the total step length. The variability, or standard deviation, for each condition was used to quantify stability. The values were averaged for each condition and related to COT for fixed and self-paced conditions.

Statistics

A repeated measures ANOVA ($P<0.05$) was used to determine if a significant effect on metabolic power and stability due to the speed and slope conditions existed.

CHAPTER 3: RESULTS

Metabolic Power

With respect to slopes, the group averaged net metabolic power increased with increasing slopes and had a quadratic relationship, as shown in Figure 5. Table 2 in Appendix B shows the coefficients of the quadratic fit equations and R^2 values for every subject and the group. The R^2 values were above 0.99 for the group, indicating good fits.

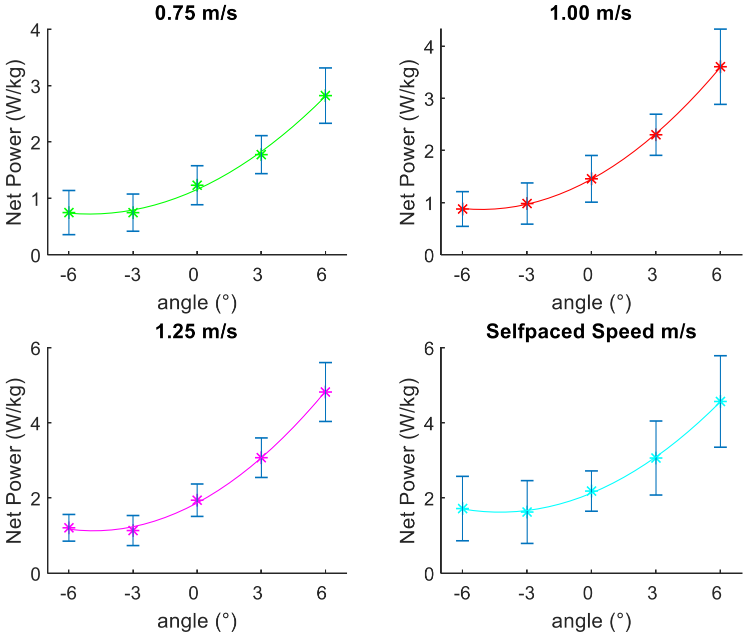


Figure 5: Net Metabolic Power as a function of slope for the group

With respect to speeds, net metabolic power increased with increasing speed regardless of slope, as shown in Figure 6. Table 3 in Appendix B shows the coefficients of the quadratic fit equations and R^2 values for every subject and the group. The self-paced speeds caused the fit using speeds to have a lower R^2 value, 0.82-0.99, for some slope conditions compared to the fit using slope that had an R^2 value over 0.99 for each speed condition. Both decline conditions had nearly the same metabolic power regardless of speed. Metabolic power increased as speed increased, independent of slope; however, the 6° incline condition had the greatest average net metabolic power regardless of speed.

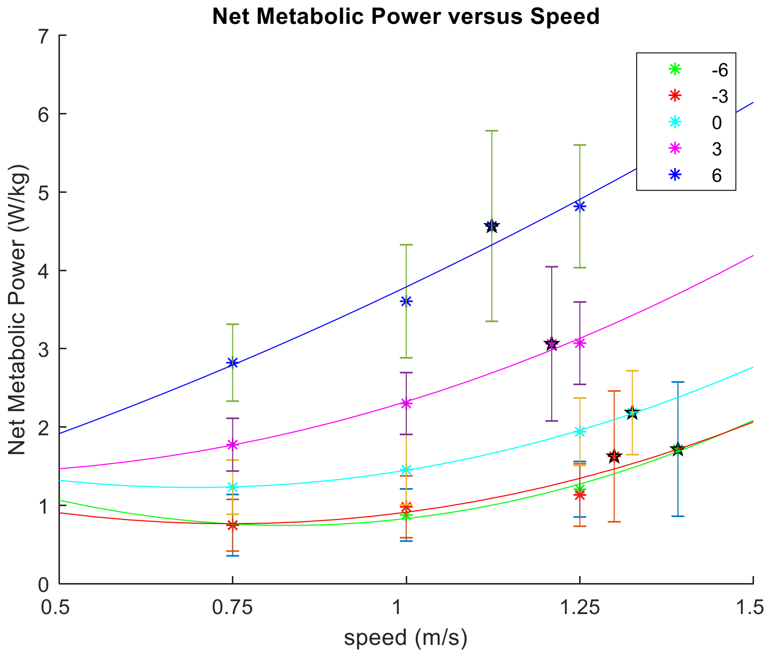


Figure 6: Net Metabolic power as a function of speed for the group

Cost of Transport

With respect to slopes, a minimum cost of transport occurred at approximately a 4° decline regardless of the speed condition, as shown in Figure 7. The cost of transport fits had a “J” shape and R^2 values over 0.99, as shown in Table 4 in Appendix B.

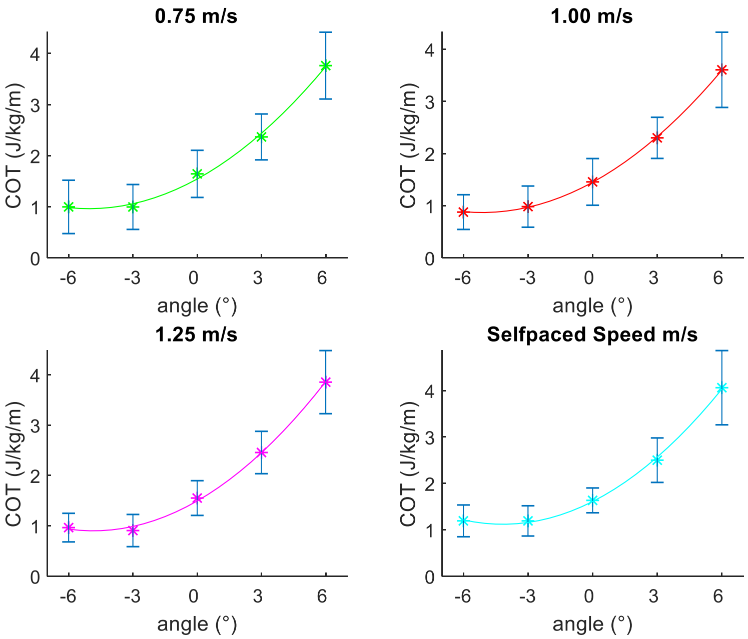


Figure 7: Cost of transport versus slope for the group

With respect to speed, most subjects walked at a speed faster than that which would minimize cost of transport, as shown in Figure 8. Subjects' self-paced speeds also tended to decrease as slope increased. For decline conditions, the walking speed needed to minimize cost of transport was faster than the incline conditions but slower than level. The cost of transport fits had a "U" shape and R^2 values over 0.98 for -6° and level, 0.82 for 3°, and below 0.25 for -3° and 6°, as shown in Table 5 in Appendix B.

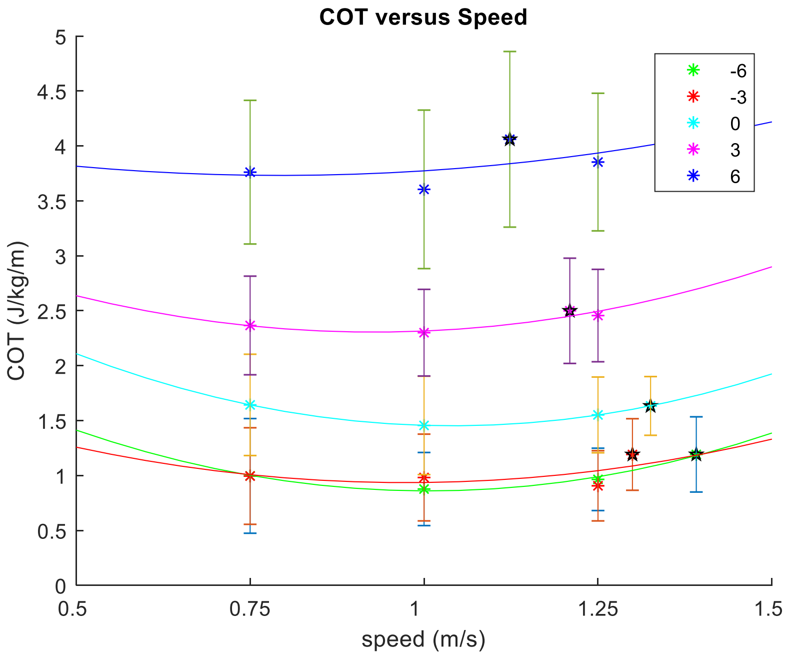


Figure 8: Cost of transport versus speed for the group

Landscape

The contour plot of speed, slope, and cost of transport showed that negative slopes have a much lower cost of transport compared to inclined slopes, as shown in Figure 9. At a given slope, the speed had little effect on cost of transport until the slopes were steeply inclined or declined. Most subjects remained near the same cost of transport level for each speed and slope condition, while a few chose speeds that resulted in higher or lower cost of transport compared to the group average.

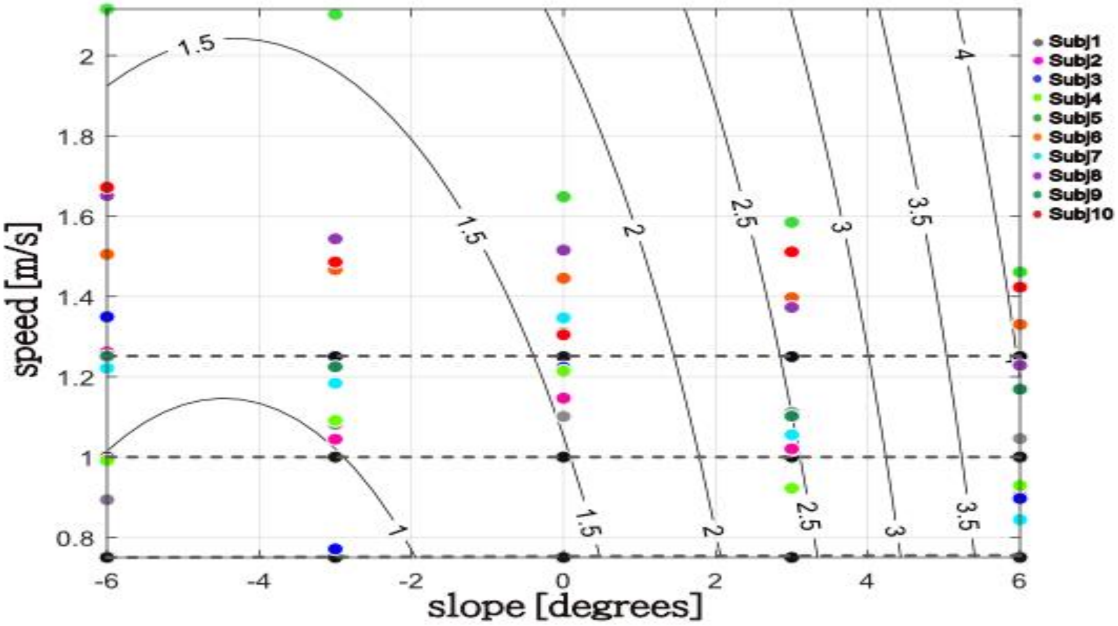


Figure 9: COT landscape as a function of speed and slope

Self-Paced Speeds

As slope increased, the range of self-paced speeds decreased for all subjects, as shown in Figure 10. For example, at -3°, the speeds ranged from 0.77-2.10 m/s. At 6°, the range was 0.84-1.46 m/s. Overall, the average self-paced speed at 6° was 15.35% slower than level ground.

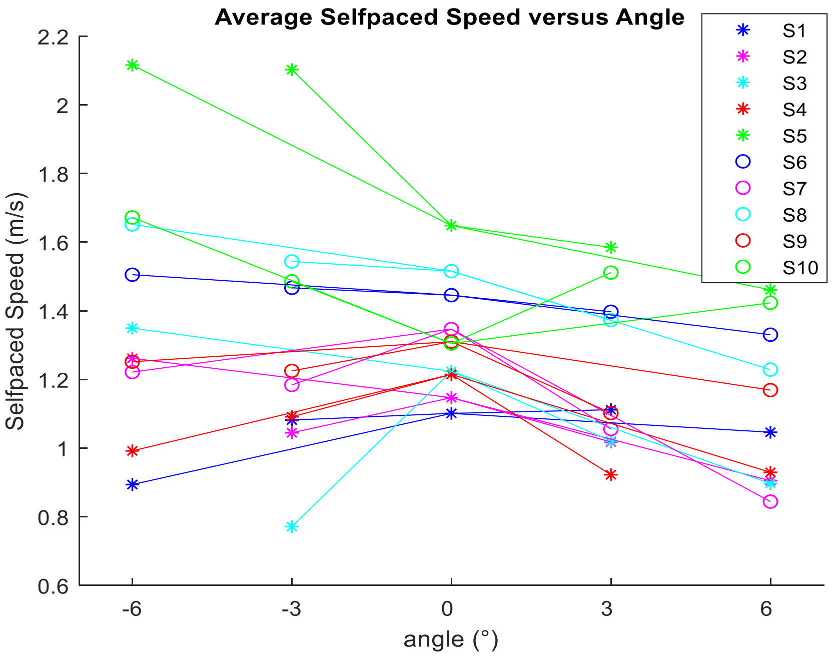


Figure 10: Average self-paced speed for each subject

Stability

Self-paced walking had the greatest step length variability, followed by 0.75 m/s, as shown in Figure 11. Overall, the variability in step length increased as slope increased. Figure 12 shows that speed had little effect on step width variability. The slowest fixed speed, 0.75 m/s, had a significantly greater stride time variability than the other speed conditions, while self-paced was similar to 1.00 m/s, as shown in Figure 13. Overall, the level of stability increased with increasing speeds.

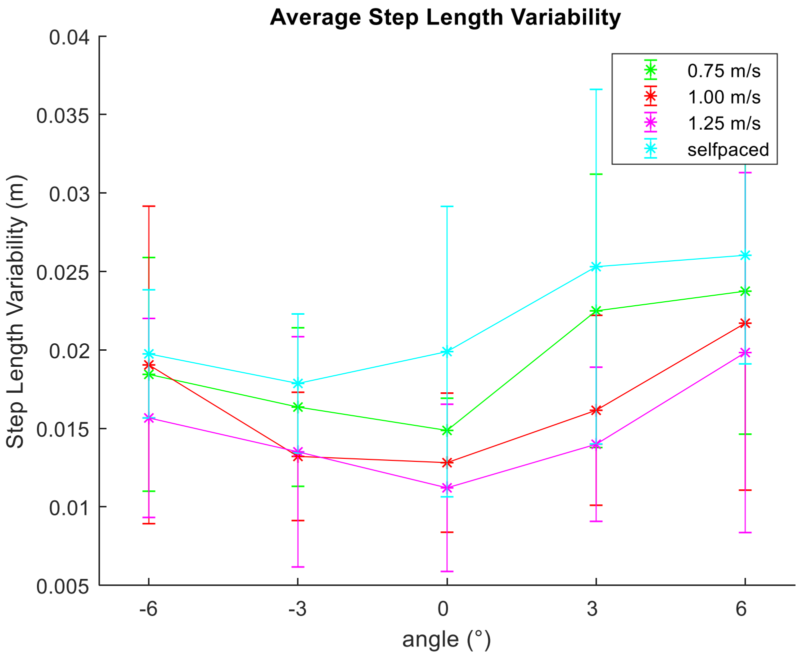


Figure 11: Average step length variability for the group

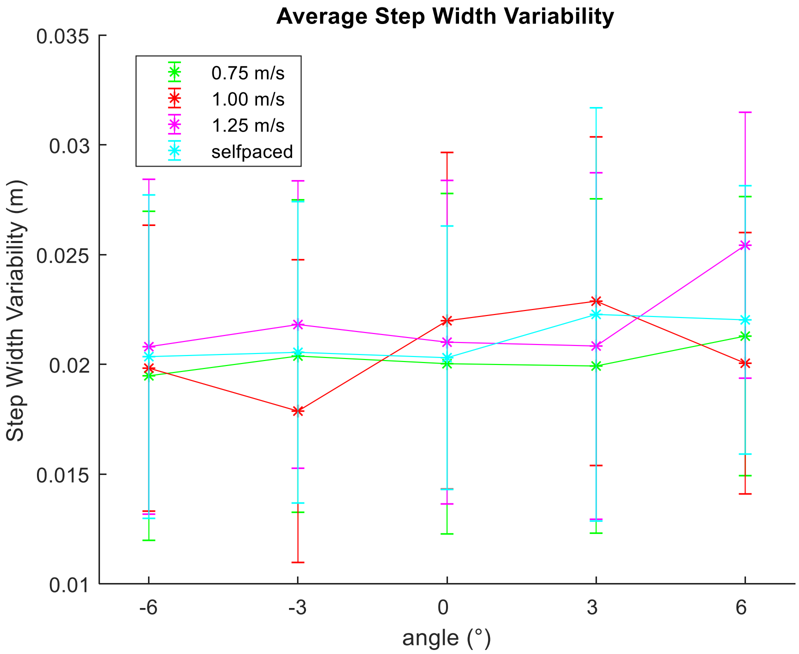


Figure 12: Average step width variability for the group

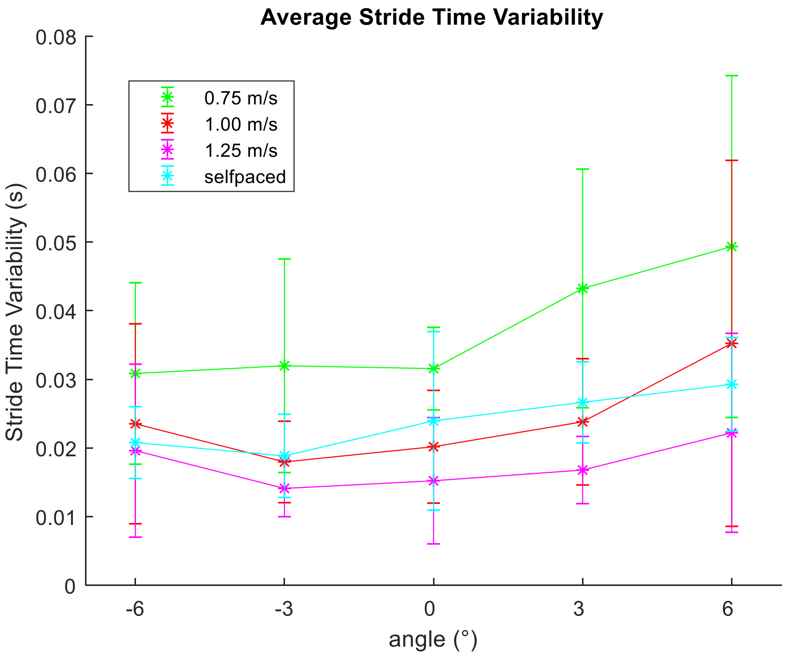


Figure 13: Average stride time variability for the group

CHAPTER 4: DISCUSSION

Metabolic power increases with increasing slope, independent of speed. The maximum power recorded was just over 5 J/kg for 1.25 m/s at a 6° incline. This is consistent with other studies which showed that greater power is needed for inclined slopes [19]. Metabolic power shows the same positive correlation with increasing speeds. Overall, as speed increases, metabolic power increases. When comparing the different slopes, the decline conditions had little difference in metabolic power, but they were both less than level. The incline conditions showed a greater jump in power compared to level. This is consistent with another study which showed that all slopes, except -6° and -3°, were statistically significant [19]. Including the self-paced speeds in the data for the fit allowed for a more accurate representation by increasing the amount of data points used. The self-paced data points showed that as slope increased, people preferred to walk at a slower speed to reduce the metabolic power at a given slope, which is supported by other literature [19]. However, the self-paced speeds did make the R^2 value lower for metabolic power fit with speed data. Ideally, the self-paced speeds would have been within the range of fixed speeds, but this was only true for the incline conditions.

Cost of transport increases with increasing slope, independent of speed. The maximum COT recorded was over 4 J/kg/m for self-paced at a 6° incline. There is a minimum COT at approximately -4°, regardless of which speed condition. This is likely due to gravity pulling subjects down the slope. Gravity allows for less energy expenditure at this slope resulting in subjects relying on passive mechanics. This observation is supported by other literature which showed that declined slopes would minimize COT due to gravity; however, people would lose stability if they fully minimized COT. Instead, people choose a more stable gait pattern that is metabolically more costly [18]. For cost of transport as a function of speed, there is not a specific speed which minimizes COT for all slope conditions. However, the speed that minimizes COT decreases as the slope increases. This shows that people must walk slower at steep inclines to lower energy expenditure. The greatest range of speeds occurs at -3°, from 0.77-2.10 m/s, whereas the smallest range of speeds occurs at 6°, from 0.84-1.46 m/s. The average self-paced speed at 6° was 15.35% lower than the average at level ground. This supports the assertion that, at -3°, subjects do not select speed based solely on metabolic cost and can choose to walk faster with little metabolic punishment. Overall, there was no significant difference between -3° and -6°, but the average self-paced speed on -6° was greater than any slope condition. Some subjects walked at self-paced speeds which minimized their COT, but the group average showed that self-paced speeds did not correlate to a minimum COT. This is likely due to factors other than metabolic expenditure, like stability. The results found are similar to other studies [2, 15].

Level of stability was quantified using variability of step length, step width, and stride time. Step length variability was greatest at a 6° incline and lowest at a 3° decline, regardless of speed. For example, in the self-paced speed condition, step length variability at a 6° incline was 30.8% greater than level, but it was 10.2% less than level for a 3° decline. Overall, step length variability increased as slope increased. Self-paced walking had the greatest variability of the speed conditions, followed by 0.75 m/s. Step width variability also increased as slope increased. However, there was no significant effect of speed on step width variability. Since people actively control step width to increase stability in the medio-lateral direction, this means that the subjects felt similar levels of stability for each speed, including self-paced [14]. Stride time variability decreased with increased speed as seen in other literature [23]. Overall, stride time variability tended to be lowest at a 3° decline. For example, in the self-paced speed condition, stride time variability at a 6° incline was 22.2% greater than level, but it was 21.3% less than level for a 3° decline. This means that while subjects could choose from a greater range of speeds at a 3° decline, there was less variation from their preferred speed compared to a 6° incline. This is likely due to increased fatigue and effort required at the steeper inclines compared to declines.

Cost of transport and stability are highly related. When people choose to actively control step mechanics like stride time, step length, and step width, it results in increased cost of transport. However, when someone prioritizes minimization of cost of transport, it can result in a lack of stability. These results show that the self-paced speeds that subjects chose were based on a combination of lowering cost of transport and maintaining stability. As slope increased, cost of transport increased, and subjects tended to actively control stability. Whereas, at a 3° decline, cost of transport was lower, and there was less variation in step length and step width. This means that at this slope, subjects did not need to actively control stability which resulted in a lower cost of transport.

The main limitation faced with this experiment was the limited range of fixed speeds tested. The fixed speeds were chosen because of an interest in studying older adults. Thus, slower speeds closer to the speeds that older adults would walk at were used. For this study however, most subjects chose a self-paced speed faster than the fastest fixed speed. Having included another fixed speed in addition to the ones tested or testing a greater range of fixed speeds up to 1.5 m/s, would have enhanced the findings of this study and more accurately portrayed the results of young adults.

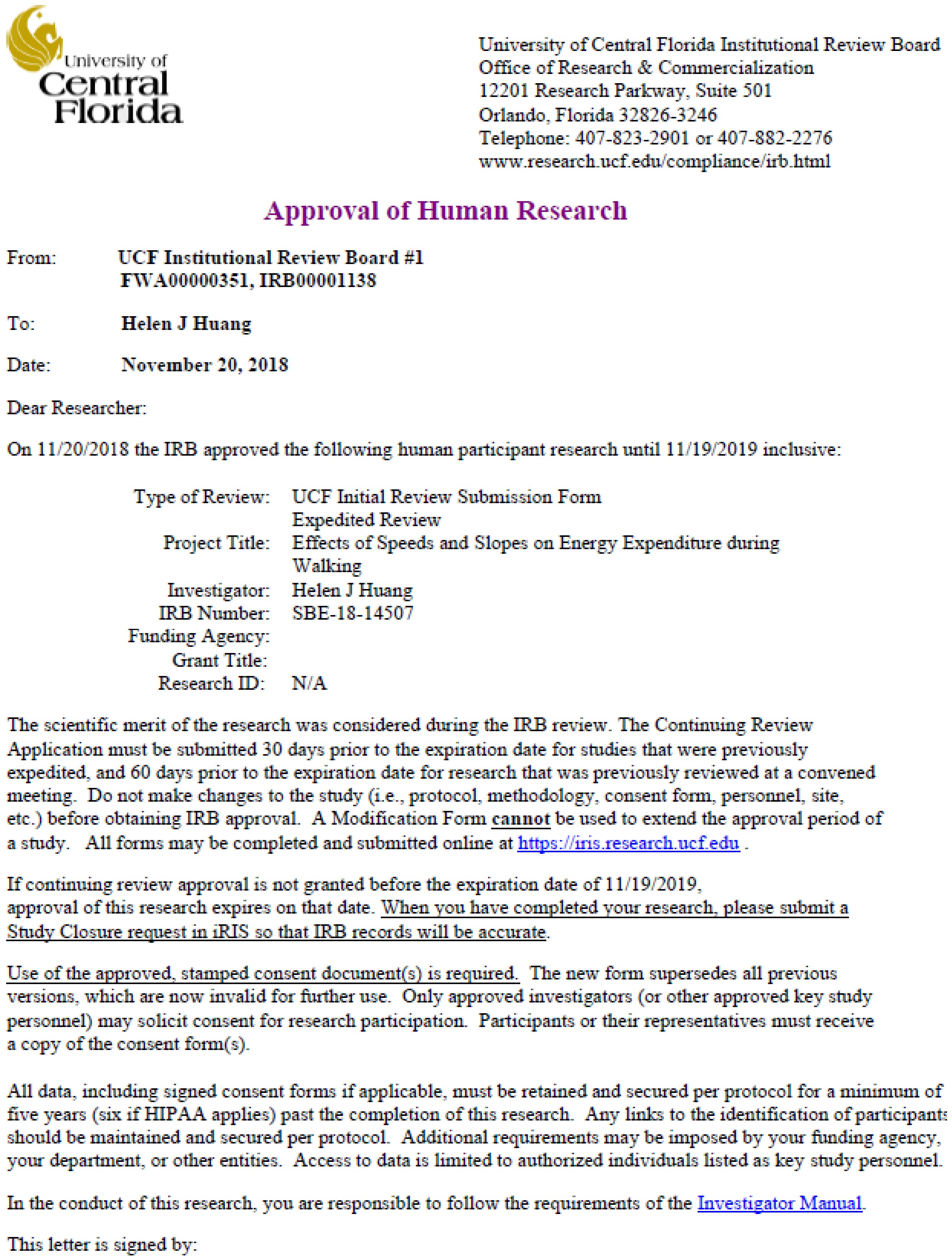
CHAPTER 5: CONCLUSION

There is no specific speed that minimizes cost of transport for all slopes. However, a slope (-4°) exists which minimizes cost of transport for most subjects. Slope had a greater effect on cost of transport than speed. Overall, cost of transport is a good indicator of effort, but it, alone, does not explain self-paced walking speeds.

Generally, subjects tended to prefer walking at speeds faster than that which would minimize the cost of transport. From the stride time variability, it was clear that people felt more stable when walking at faster speeds. This is supported by the step length variability results which showed that stability decreased at steeper inclines and subjects needed to walk at slower speeds to reduce cost of transport. At decline conditions, subjects could choose from a range of speeds with little effect on metabolic cost. Subjects tended to show less variability with step length, step width and stride time at decline conditions which explains why these slopes were preferred over inclines. Overall, subjects selected their self-paced speeds at different slope conditions based on both cost of transport and level of stability.

It would be interesting to compare the results of older adults to that of younger adults in the future. Using the self-paced walking results and the preferred slope information, we plan to create a treadmill function in which self-paced speed determines which slope a person walks at. This would allow us to compare preferences for speed, stability, and slope.

APPENDIX A: IRB APPROVAL LETTER



University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Helen J Huang**

Date: **November 20, 2018**

Dear Researcher:

On 11/20/2018 the IRB approved the following human participant research until 11/19/2019 inclusive:

Type of Review: UCF Initial Review Submission Form
Expedited Review
Project Title: Effects of Speeds and Slopes on Energy Expenditure during Walking
Investigator: Helen J Huang
IRB Number: SBE-18-14507
Funding Agency:
Grant Title:
Research ID: N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30 days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu .

If continuing review approval is not granted before the expiration date of 11/19/2019, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

This letter is signed by:

Signature applied by Jessica Jacques on 11/20/2018 02:37:21 PM EST

Designated Reviewer

APPENDIX B: FIT COEFFICIENT TABLES

Table 2: Metabolic power as a function of slope fit coefficients

	speed	*a*	*b*	*c*	*R^2*
1	0.75 m/s	0.02063	0.1525	1.395	0.9984
	1.00 m/s	0.01041	0.2502	1.519	0.9695
	1.25 m/s	0.0442	0.2809	1.409	0.9958
	selfpaced	0.03722	0.3238	1.797	0.9932
2	0.75 m/s	0.007484	0.1654	1.348	0.8827
	1.00 m/s	0.0215	0.2025	1.368	0.9905
	1.25 m/s	0.03448	0.2587	1.882	0.9871
	selfpaced	0.02221	0.1479	1.395	0.9344
3	0.75 m/s	0.01052	0.1307	1.03	0.9849
	1.00 m/s	0.01743	0.185	1.281	0.982
	1.25 m/s	0.02689	0.2943	1.724	0.9887
	selfpaced	0.01471	0.1069	1.384	0.6902
4	0.75 m/s	0.01901	0.222	1.032	0.9969
	1.00 m/s	0.0554	0.316	1.165	0.9713
	1.25 m/s	0.05097	0.396	1.725	0.9993
	selfpaced	0.03358	0.2874	1.541	0.9023
5	0.75 m/s	0.01269	0.134	0.692	0.9984
	1.00 m/s	0.01592	0.1919	0.863	0.9733
	1.25 m/s	0.03314	0.2948	1.25	0.9859
	selfpaced	0.03348	0.1549	3.116	0.8094
6	0.75 m/s	0.02716	0.1843	0.7058	0.9735
	1.00 m/s	0.02404	0.2166	1.278	0.8961
	1.25 m/s	0.008704	0.2116	1.708	0.9354
	selfpaced	0.02212	0.2644	2.115	0.9293
7	0.75 m/s	0.003713	0.2293	1.48	0.9507
	1.00 m/s	0.02467	0.2544	1.709	0.9104
	1.25 m/s	0.03062	0.362	1.998	0.9874
	selfpaced	-0.00782	0.2257	2.377	0.8635
8	0.75 m/s	0.02532	0.2095	1.267	0.9987
	1.00 m/s	0.009499	0.1762	1.803	0.9736
	1.25 m/s	0.0189	0.3387	2.437	0.9976
	selfpaced	0.02896	0.3009	3.051	0.9905
9	0.75 m/s	0.01839	0.1791	1.361	0.8857
	1.00 m/s	0.02122	0.2401	1.787	0.9434
	1.25 m/s	0.03851	0.341	2.368	0.9797
	selfpaced	0.04398	0.292	1.918	0.9443
10	0.75 m/s	0.02585	0.1183	1.257	0.9786
	1.00 m/s	0.01975	0.2254	1.707	0.9895
	1.25 m/s	0.02815	0.2753	2.167	0.944

	selfpaced	0.05041	0.2736	2.588	0.8963
Overall	0.75 m/s	0.017077	0.17251	1.15678	0.9963
	1.00 m/s	0.021984	0.22583	1.448	0.9998
	1.25 m/s	0.031456	0.30533	1.8668	0.9982
	selfpaced	0.027885	0.23775	2.1282	0.999

Table 3: Metabolic power as a function of speed fit coefficients

	slope	*a*	*b*	*c*	R^2
1	-6	10.11	-20.32	10.9	0.5585
	-3	-0.3754	0.4456	0.9575	0.1146
	0	-3.607	7.371	-2.052	0.8086
	3	-3.26	8.16	-2.365	0.3942
	6	-4.38	12.31	-3.755	0.6482
2	-6	2.814	-4.244	2.418	0.9564
	-3	1.058	-0.5805	0.3335	0.98
	0	8.099	-15.02	8.189	0.9641
	3	4.099	-6.934	5.081	0.9585
	6	4.14	-3.797	2.985	0.9987
3	-6	3.437	-6.068	3.294	0.791
	-3	0.8119	-0.3414	0.465	0.9591
	0	2.467	-3.448	2.127	0.8746
	3	4.211	-5.927	3.72	0.947
	6	6.06	-7.441	4.305	0.9986
4	-6	-2.913	6.042	-2.904	0.8913
	-3	-8.925	18.79	-8.599	0.9562
	0	10.21	-18.9	9.545	0.9435
	3	2.807	-2.246	1.866	0.9448
	6	-11.03	27.71	-11.49	0.9974
5	-6	1.631	-2.508	1.296	0.9995
	-3	2.225	-4.133	2.229	0.9994
	0	2.519	-4.055	2.303	0.9981
	3	2.464	-2.074	1.419	1
	6	3.204	-2.372	1.849	0.9849
6	-6	0.9584	-1.322	0.9705	0.9985
	-3	0.32	0.758	-0.155	0.6826
	0	-0.5569	3.478	-1.486	0.9865
	3	1.306	-0.8018	1.114	0.9998
	6	2.295	-2.504	3.576	0.594
7	-6	-10.22	21.71	-10.19	0.9771
	-3	1.989	-3.052	1.654	0.8414

	0	2.827	-4.566	3.685	0.8398
	3	-2.123	6.999	-1.976	0.9942
	6	1.822	0.7856	1.372	0.9999
8	-6	1.839	-3.041	2.202	0.9505
	-3	2.551	-3.916	2.45	0.9951
	0	-0.1581	2.81	-0.7583	0.9952
	3	3.286	-3.688	2.972	0.9664
	6	20.26	-36.05	19.07	0.8649
9	-6	3.703	-5.843	3.054	0.9983
	-3	-0.4095	1.988	0.09966	0.9835
	0	-0.5529	2.565	-0.2247	0.7459
	3	2.338	-1.171	1.189	0.9947
	6	7.052	-8.604	5.782	0.9924
10	-6	3.488	-6.701	4.529	0.9696
	-3	2.057	-3.679	2.617	0.9293
	0	2.176	-2.686	2.177	0.9997
	3	0.2842	3.055	-0.6215	0.9999
	6	2.803	-2.004	2.832	0.9975
Overall	-6	2.981	-4.945	2.793	0.9863
	-3	2.293	-3.427	2.046	0.8166
	0	2.379	-3.312	2.38	0.999
	3	2.019	-1.315	1.62	0.9913
	6	0.9685	2.293	0.5264	0.9602

Table 4: COT as a function of slope fit coefficients

	speed	*a*	*b*	*c*	R^2
1	0.75 m/s	0.02751	0.2034	1.859	0.9984
	1.00 m/s	0.01041	0.2502	1.519	0.9695
	1.25 m/s	0.03536	0.2247	1.127	0.9958
	selfpaced	0.04166	0.2917	1.587	0.9966
2	0.75 m/s	0.01001	0.2207	1.797	0.883
	1.00 m/s	0.02152	0.2026	1.368	0.9905
	1.25 m/s	0.02759	0.207	1.506	0.9871
	selfpaced	0.0261	0.1887	1.274	0.99
3	0.75 m/s	0.01403	0.1743	1.373	0.9849
	1.00 m/s	0.01743	0.185	1.281	0.982
	1.25 m/s	0.02151	0.2355	1.379	0.9887
	selfpaced	0.01706	0.1444	1.284	0.9632
4	0.75 m/s	0.02535	0.296	1.376	0.9969
	1.00 m/s	0.0554	0.316	1.165	0.9713

	1.25 m/s	0.04078	0.3168	1.38	0.9993
	selfpaced	0.04412	0.3207	1.372	0.9405
5	0.75 m/s	0.01692	0.1787	0.9226	0.9984
	1.00 m/s	0.01592	0.1919	0.863	0.9733
	1.25 m/s	0.02651	0.2358	0.9996	0.9895
	selfpaced	0.02234	0.1683	1.779	0.9514
6	0.75 m/s	0.03621	0.2457	0.9411	0.9735
	1.00 m/s	0.02404	0.2166	1.278	0.8961
	1.25 m/s	0.006963	0.1692	1.366	0.9354
	selfpaced	0.01897	0.2066	1.456	0.9339
7	0.75 m/s	0.00495	0.3057	1.973	0.9507
	1.00 m/s	0.02467	0.2544	1.709	0.9104
	1.25 m/s	0.0245	0.2896	1.599	0.9874
	selfpaced	0.01291	0.2783	1.884	0.972
8	0.75 m/s	0.03376	0.2794	1.689	0.9987
	1.00 m/s	0.009499	0.1762	1.803	0.9736
	1.25 m/s	0.01512	0.271	1.95	0.9976
	selfpaced	0.02992	0.2784	2.028	0.9876
9	0.75 m/s	0.02452	0.2388	1.815	0.8857
	1.00 m/s	0.02122	0.2401	1.787	0.9434
	1.25 m/s	0.03081	0.2728	1.895	0.9797
	selfpaced	0.03864	0.2626	1.582	0.9631
10	0.75 m/s	0.03447	0.1577	1.677	0.9786
	1.00 m/s	0.01975	0.2254	1.707	0.9895
	1.25 m/s	0.02252	0.2202	1.733	0.944
	selfpaced	0.02989	0.2089	1.837	0.9478
Overall	0.75 m/s	0.0227	0.23	1.542	0.9963
	1.00 m/s	0.02199	0.2258	1.448	0.9998
	1.25 m/s	0.02516	0.2443	1.493	0.9982
	selfpaced	0.02816	0.2349	1.608	0.9987

Table 5: COT as a function of speed fit coefficients

	slope	*a*	*b*	*c*	R^2
1	-6	11.33	-24.11	13.46	0.7119
	-3	1.265	-3.928	3.685	0.7535
	0	-2.237	3.052	0.8965	0.9571
	3	-1.478	2.204	1.772	0.1233
	6	-3.425	6.463	1.116	0.064
2	-6	2.604	-4.979	3.361	0.7515
	-3	0.3111	0.07999	0.4213	0.9152

	0	8.361	-17.32	10.25	0.9844
	3	5.355	-12.033	8.924	0.9707
	6	3.238	-5.51	5.595	0.9859
3	-6	2.727	-5.508	3.477	0.4906
	-3	0.5831	-0.8492	1.197	0.4575
	0	2.436	-4.673	3.377	0.3816
	3	3.878	-7.512	5.642	0.5934
	6	4.87	-8.264	6.302	0.9794
4	-6	-3.09	7.084	-3.049	0.7592
	-3	-8.741	17.71	-7.729	0.9639
	0	10.38	-20.72	11.18	0.8909
	3	2.37	-3.933	3.976	0.5198
	6	-12.76	26.73	-8.761	0.97
5	-6	0.7026	-1.193	0.9368	0.9906
	-3	1.205	-2.612	1.777	0.9854
	0	1.566	-3.075	2.312	0.9993
	3	1.049	-1.166	1.944	0.999
	6	1.936	-2.763	3.504	0.8818
6	-6	0.7511	-1.585	1.453	0.9994
	-3	-0.7933	2.245	-0.4944	0.2462
	0	-1.081	3.169	-0.6736	0.9455
	3	0.9861	-1.865	2.504	1
	6	2.344	-6.113	7.201	0.4192
7	-6	-10.99	22.6	-10.31	0.9683
	-3	1.964	-3.698	2.319	0.4565
	0	3.136	-7.36	6.202	0.8033
	3	-2.01	4.001	0.9041	0.7556
	6	1.536	-2.706	1.145	0.9779
8	-6	1.361	-3.173	2.853	0.6984
	-3	1.794	-3.654	2.978	0.9902
	0	-0.7025	2.099	0.4951	0.9014
	3	3.203	-6.387	5.746	0.5706
	6	20.9	-41.86	24.22	0.6903
9	-6	3.256	-6.067	3.725	0.9926
	-3	0.06761	-0.6498	2.262	0.9462
	0	0.2125	-0.7746	2.329	0.2011
	3	1.125	-1.176	2.413	0.9566
	6	6.337	-11.77	9.659	0.8615
10	-6	3.308	-8.115	6.181	0.7886
	-3	1.943	-4.604	3.691	0.8773
	0	2.232	-4.625	4.061	0.9795

	3	-0.5136	1.99	1.237	0.9966
	6	2.325	-4.874	6.207	0.9426
Overall	-6	2.161	-4.348	3.047	0.9811
	-3	1.434	-2.794	2.297	0.275
	0	2.242	-4.669	3.883	0.9999
	3	1.814	-3.365	3.866	0.828
	6	0.9763	-1.549	4.346	0.2141

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