

# Research Proposal Project

## *Walking Uphill Efficiently With A Load*

MCEN 4228-5228-015: Modeling Human Movement

Group 3

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## **Specific Aims**

Uphill walking requires more energy to be used in comparison to level walking and the demand is even greater when a load, such as a backpack, is being carried. This research will develop an informative approach on how humans can make a hill climb less strenuous when carrying a load. This will be accomplished by understanding the mechanics around uphill walking and how certain parameters such as load weight, incline grade, and center of mass location, can affect metabolic costs. It is important to note that there is very little research done on uphill walking with a load. Some studies look at pure uphill walking to observe the costs and work the human body puts in to carry itself up a hill. This research is then used in future studies to develop exoskeletons that assist in muscle actuation and shoe modifications that change how the foot interacts with sloped surfaces.

Furthermore, there is research on the costs of carrying a load on level ground, which looks at the adjustments the human body makes to compensate for the added load and the increased costs for carrying a load, leading studies to make modifications and design different backpacks that try to reduce this cost. With little research done on uphill walking with a load, there are not many methods that look to reduce the costs of loaded uphill walking. Thus, hypotheses for what affects loaded uphill walking will be formed based on what is known about unloaded uphill walking and loaded level walking.

With these prior findings in mind, our research will address three key aims for walking uphill efficiently with a load. The first aim is to understand how metabolic cost changes with load and slope/grade. Our hypothesis for this is that metabolic costs for walking uphill with a load increases as the slope grade of the hill and/or the load being carried increases. Our next aim looks at how the location of the center of mass (COM) can affect metabolic costs. We hypothesize that the further a load's COM is moved from the human's COM, the higher the metabolic cost will be. Our last aim looks at how implementing a heel wedge can affect metabolic costs. The influence of heel height on kinematics and gait during level walking has been studied extensively. However, while walking uphill, a heel wedge that negates the slope reduces metabolic cost. We hypothesize that a heel wedge that brings an uphill slope closer to level walking will reduce metabolic cost while walking with a backpack load.

Strategies to reduce cost can be derived based on the significant changes the human body makes in uphill walking with a load. We believe our research can be used to develop assistive methods and/or devices with respect to human biological capacities to reduce costs for loaded uphill walking. Several notable innovations aimed to reduce the metabolic cost of carrying loads that are already on the market are the Hover Glide backpack, Aarn Balance Packs, and the ExoTi backpack by Vargo.

## Background & Significance

Uphill walking has a greater metabolic cost than walking on level ground. Humans will alter their gait by reducing their walking speed, cadence, and step length to reduce energy expenditure as the incline becomes more strenuous.<sup>[1,5,13]</sup> These reductions are a result of the demand from potential energy and a sense of caution for possible slippage at toe-off.<sup>[5]</sup> The leading leg for uphill walking will perform positive work as it assists the trailing leg to raise the COM with each step. Both legs generate more power at double support to exert greater propulsive forces.<sup>[13]</sup> Tests in a laboratory environment, where speed is kept constant in both level and uphill walking found an increase in knee power generation, and greater muscle activity primarily in the knee, hip, and ankle extensor muscles as slope grade increased.<sup>[6,20]</sup> Oxygen consumption is also found to have a direct proportionality to hill gradient, which has led metabolic cost data to portray a linear trend with slope grade.<sup>[12]</sup> (Figure 1) Past studies have mainly focused on the metabolic cost increase when either walking on inclined planes or with a backpack load. There is significantly lesser data available on how such a load affects human gait and energy expenditure during uphill walking.

Prior research on backpack loads has concluded that there is a linear relationship between added load and the increase in metabolic cost.<sup>[14]</sup> There is also evidence that suggests that modifying the center of mass of subjects carrying a load on their back can also affect energy expenditure.<sup>[21]</sup> Despite both load and center of mass affecting gait and metabolic cost, their interaction together while walking up an incline has not been studied extensively. With our research, we plan to study the dynamics of this novel environment in greater detail.

In a similar vein, the impact of heel wedges has been studied extensively in level walking<sup>[11,15-18]</sup> and much of the research has been focused on the effects of high heeled shoes<sup>[15-18]</sup>. Joint moments show a graded response as heel height increases.<sup>[16]</sup> Meanwhile, experiments with heel wedges have been shown that they do not hinder foot kinematics significantly<sup>[10]</sup>. They have also shown potential in redistributing loads among the triceps surae.<sup>[11]</sup> In uphill walking, heel wedges which negate the slope of the treadmill have shown to reduce the metabolic cost.<sup>[11]</sup> The optimal treadmill grade minimized the COM work rate and propulsive ground reaction forces. Thus, heel wedges can potentially improve comfort and save energy. However, the effect of such wedges on joint kinematics while walking with a load remains largely unstudied. The results obtained from studying these effects can be used to optimize footwear based on metabolic rate or joint moments.

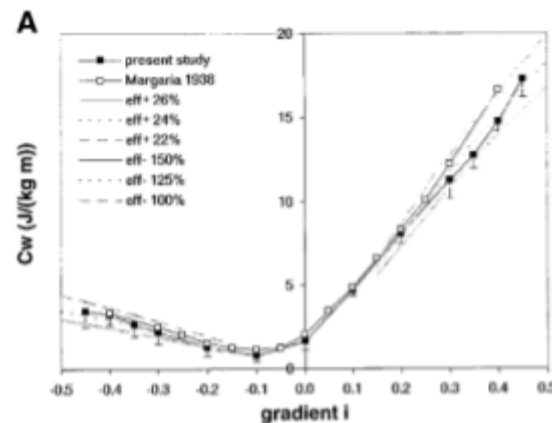


Figure 1: Energy Cost of Walking At Different Gradients  
A. Minetti, et. al; "Energy cost of walking and running at extreme uphill and downhill slopes" pg. 3; 29 Nov. 2002

Following the literature review, it is evident that there are very few studies focusing on the novel environment of uphill walking with a backpack load. We believe that the data gathered from our research can be used for developing strategies to reduce metabolic cost or improve comfort while walking uphill, provide insight into efficient backpack positioning, and potentially have been used for designing walkways on campuses with suitable inclines for backpack carrying students.

### **Research Approach**

We have three specific aims for our research proposal. First, determining and analyzing the metabolic cost during walking uphill with a load on the back. Second, understanding the effect of the center of mass displacement on metabolic cost while walking on an inclination with a load. Lastly, we want to analyze how walking uphill with heel wedges affects metabolic cost.

We will be conducting our experiments on 10 healthy male participants (mean  $\pm$  SD age  $25 \pm 5$  years, weight  $70 \pm 10$  kg, and height  $172 \pm 10$  cm). Participants' resting metabolic rate will be determined in 3 minutes by standing on a treadmill. The walking speed on the treadmill will be kept constant for all testing at 1.0 m/s, and each trial will be 6 minutes long with the last minute being used for data collection to calculate the metabolic cost. For establishing the baseline, subjects will walk level and incline grades with no load. The incline angles that will be tested across all hypotheses are  $4^\circ$ ,  $8^\circ$ , and  $12^\circ$ . In the second case, a constant load will be distributed around the backpack to change the COM. For the third hypothesis, we will analyze the effect of different heel wedges on metabolic cost.

Instrumented dual-belt treadmill with two six degrees of freedom force plates (R-mill, Forcelink, the Netherlands) will be used to measure the ground reaction forces. Joint motion data will be collected using a motion capture system with 10 Osprey cameras and Cortex software (Motion Analysis, CA). 27 markers will be placed on the lower limb of each individual. Indirect calorimetry will be used to calculate the metabolic cost. Pulmonary gas exchange rates will be measured with the COSMED K4b2 system (COSMED, Italy).

### **Study 1:**

#### **Observing Metabolic Cost At Different Loads And Slope Grades**

This section aims to understand how metabolic cost for walking changes at different iterations of slope grades and loads using unloaded, level walking as a baseline comparison. We hypothesize that as the slope incline increases, the metabolic cost will increase and as load increases, the metabolic cost will still increase. We expect to see the greatest costs at the highest slope testing grade while carrying the heaviest testing load.

As stated in the overview, a dual-belt treadmill with force sensors will be used to test subjects at various slope grades:  $0^\circ$  (level),  $+4^\circ$ ,  $+8^\circ$ , and  $+12^\circ$ . These angles were chosen based on both the angle limit the treadmill can go and on angle settings from past research that tested metabolic costs for uphill walking.<sup>[1,5,11,12]</sup> Force sensors are required since ground reaction

forces (GRF) will change as the slope grade is adjusted and joint kinematic data will be used to observe the changes in joint moments. The knee moment is expected to change the most from prior research.<sup>[6,20]</sup> Both legs are expected to generate more force at double support for steeper inclines.<sup>[13]</sup>

Subjects will also be tested with 0%, 5%, 10%, 15% additional bodyweight strapped to their back using the backpack that is stated in the overview. Prior research for various load-carrying tests has led us to expect large changes in ankle and hip moments, and a greater pelvic lean as the carried load becomes heavier.<sup>[7,21,22]</sup>

This test will go through a total of 16 iterations with 4 different slope grades (level, +4°, +8°, and +12°) and 4 different loads (+0%, +5%, +10%, +15% body weight). Although this may seem like many tests, there is a very scarce amount of data for loaded uphill walking. All hypotheses so far are based on unloaded uphill walking and loaded level walking so acquiring data for various slopes and loads will show what has a greater significance for affecting metabolic costs. The metabolic and kinematic data obtained from the baseline test of level walking with a 0% additional load (unloaded) will be re-collected at the start for the following two studies as well.

Subjects will complete four testing sessions on four different days. Each day will begin with a 5-minute warm-up session that requires them to walk on the treadmill at a level slope grade of 1.0 m/s. Afterward, subjects will be required to walk at the specified slope grade and load weight which will be determined at random for 6 minutes at 1.0 m/s. Each subject will perform this test four times a day at a different slope and load, with 6-minute breaks in between. By the end of the fourth testing day, there will be 16 iterations of slope and load walking data for each test subject. The data collection method is the same as what is stated in the main overview.

## **Study 2:**

### **Metabolic Cost of Load Distribution**

The section aims to study the metabolic cost and joint kinematics of carrying loads in different positions along the sagittal plane while walking up to various slopes. We hypothesize that the further the load is moved from the mid-coronal plane along the sagittal plane, the greater the metabolic cost will be. We suspect that the increases in metabolic cost will be primarily due to the changes in the musculoskeletal geometry to balance the new COM.

When analyzing the human gait as an inverse pendulum, the individual's COM must reach an apex halfway through the stance phase to move forward. When the COM is moved forward or backward on the sagittal plane, the individual must adjust their body position to stay balanced, then use this new position to walk. Previous studies indicate that most of the repositioning when the COM is moved along the sagittal plane takes place at the pelvis or the ankles<sup>[14,21,22]</sup>. These adjustments to the musculoskeletal geometry will affect the forces acting on the muscles, hence affecting metabolic consumption. The experiment will analyze the joint kinematics and metabolic cost of moving the individual's COM forward and backward on the sagittal plane.

This experiment will have each participant walk at 1.0 m/s on a treadmill at 0°, 4°, 8°, and 12° above a horizontal plane with three different loading conditions. Each loading condition will weigh 10% of the subject's weight. The first condition will have the load carried in a bilateral backpack on the back, the second condition will have the same loaded backpack on the participants front, and the third condition will be splitting the load between two backpacks, one on the front and one on the back (Figure 2). We will make sure that the backpack(s) is positioned at the same height on the torso in every condition. We expect that the metabolic cost will be higher when the load is carried on the front or the back compared to being distributed between the two. When the load is on the back, we expect the participants to have a forward pelvic tilt, and a forward lean at the ankles. When the load is on the front, we expect a backward tilt at the participants' pelvis.



Figure 2: Load Conditions  
Created by: Colten Meisner

### **Study 3:**

#### **Effect of Heel Wedges on Metabolic Cost in Uphill Walking**

The aim of this section is to study how varying the outsole angle of footwear and treadmill incline while walking with a backpack load can affect the metabolic cost, joint kinematics, and muscle activity. We hypothesize that the footwear angle which negates the slope of this treadmill incline will minimize the metabolic cost.

To vary the footwear angle, we aim to develop a shoe that varies the outsole angle without significantly affecting damping or bending stiffness. While varying these parameters could potentially affect GRFs and joint kinematics, we will focus only on the effect of the sole angle. We plan to use a conventional shoe with a completely flat outsole (Chuck Taylor All Star, Converse) of 3 different sizes (9.5, 10, 10.5 US) with hardboard wedges attached to the outsole. Grip rubber can be glued to the bottom to prevent slipping. Depending on the thickness of the hardboard, counterweights may need to be attached to the top of the shoe.

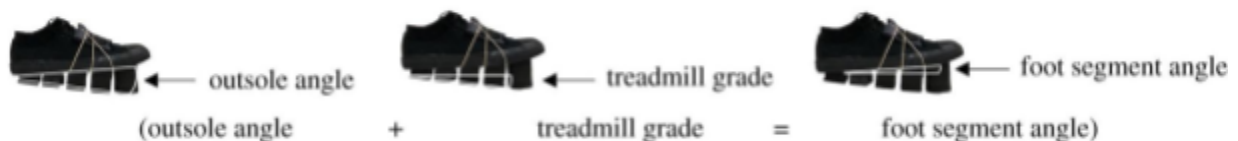


Figure 3: Antonellis, Prokopios, et al. "Modular footwear that partially offsets downhill or uphill grades minimizes the metabolic cost of human walking." Royal Society open science 7.2, pg.4 (2020): 191527.

The treadmill angles used are similar to the prior two hypotheses, and the backpack load is set at 10% of the subject's body weight. From previous research, we concluded that sagittal plane biomechanical parameters, namely ankle kinetics have the greatest effect on metabolic cost in uphill walking<sup>[11]</sup> (since the variation of the slope also occurs along the sagittal plane). The soleus muscle has been seen to have the highest energy expenditure<sup>[11]</sup>, thus EMG activity could potentially be used to relate metabolic cost to soleus muscle activity.

We will test 8 combinations of 3 different treadmill gradients and 4 outsole angles. The treadmill grade is expected to have a greater effect on the metabolic cost than the heel wedge, which is why an additional outsole angle is considered. The heel angles are selected based on our hypothesis that negating the slope will cause a decrease in metabolic cost. A positive incline of the treadmill, i.e. uphill walking is taken as positive, and the angles considered are 4°, 8°, and 12°. Heel wedges that negate this uphill slope are taken as negative angles and the values considered are -4°, -6°, -8°, -12°, with the added constraint that the heel wedge angle should not exceed the treadmill grade.

All trial values obtained during this phase will be compared against a baseline established similarly to hypothesis one to study the interaction of heel wedges while walking uphill with a load. If we take the foot segment angle as the sum of the treadmill grade and the heel wedge angle (Figure 3), then we expect to see the metabolic cost to be minimum when this foot segment angle is close to 0 (Figure 4).

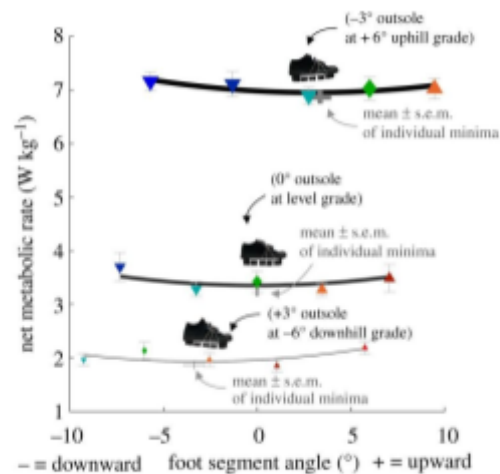


Figure 4: Antonellis, Prokopios, et al. "Modular footwear that partially offsets downhill or uphill grades minimizes the metabolic cost of human walking." *Royal Society open science* 7.2 (2020): 191527.

## Statistics

The mean and standard deviation of the weight of the participants, the loads the participants will carry, and the metabolic cost will be calculated to summarize and organize the characteristics of our data set. The variance will be calculated for metabolic cost during level and uphill walking, before and after load carrying, and before and after using heel wedges to see the effects for our hypothesis testing. Boxplots will be used to visualize the distribution of measured metabolic costs and identify outliers. Standard deviation will be used to detect and remove outliers from the metabolic cost data. If our groups of data came to be dependent using correlation analysis, we will conduct a Repeated Measures ANOVA test. If our groups of data are independent, the Anderson-Darling test will be used to check whether our data is normally distributed. If our data is not normally distributed we will use the Kruskal-Wallis rank ANOVA test. If our groups of normally distributed data have equal variance determined using Levene's test for variance, we will use the classical Fisher's ANOVA test to determine whether the differences between groups

of data are statistically significant. If the groups of data have unequal variance, we will use Welch's ANOVA test to determine the statistical significance. For our research project, we will be using a 95% confidence interval and if we get a lesser p-value we will reject our null hypothesis and consider our results statistically significant. Pearson correlation test will be used to determine the correlation between our parameters i.e. load, inclination, and heel angle, and the target variable, namely the metabolic cost. Finally, Cohen's effect size criteria will be used to indicate the practical significance of our results for the correlational as well as experimental analysis.

### **Potential Complications**

1. Due to the laboratory setting, and subjects' inability to alter backpack straps or own walking speed, the metabolic cost established during baseline studies cannot be considered identical to a natural outdoor setting.
2. The effectiveness of wedged shoes when on flat ground.
3. The effects of the heel wedges and the backpack load during inclined walking may interfere with each other.

### **Timeline**

Phase	Details	Timeframe (in months)			
		<b>22-24 months</b>			
<b>1. Location and Setup</b>	Find testing location, set-up required equipment	<b>2</b>			
<b>2. Design</b>	Acquire and design backpacks and shoes w/ wedges		<b>1</b>		
<b>3. Recruitment</b>	Recruit study participants			<b>1</b>	
<b>4. Data Collection</b>	Acclimatisation, experimental trials, and data collection			<b>6</b>	
<b>5. Data Analysis</b>	Data analysis for metabolic cost, joint kinematics, parameter significance, and correlation				<b>6-8</b>
<b>6. Report</b>	Write up the results obtained				<b>6</b>



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