METABOLIC COST CONTRIBUTIONS OF WEIGHT AND MASS IN SLOPED WALKING

by

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Metabolic Cost Contributions of Weight and Mass in Sloped Walking
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The metabolic power required to walk over level ground is determined by two primary mechanical tasks: body weight (BW) support and work done on the center of mass. However, it is not yet known how weight and mass contribute to metabolic power with varying uphill and downhill slopes. We hypothesized that BW and mass would each require significant, but opposing metabolic contributions to walk on uphill versus downhill slopes. We tested our hypotheses by measuring metabolic rates in 10 healthy subjects as they walked for 5 minutes under four general conditions: unaltered (UA), with reduced weight using simulated reduced gravity, added weight, and added mass alone. Participants walked under each of these conditions on level ground (0°), uphill (+3° and +6°), and downhill (-3° and -6°) slopes. We found that the percentage of net metabolic power (NMP) due to BW increased significantly from 19 ± 18.4% on level ground up to 77 ± 7.5% at +6°. Whereas the percentage of NMP due to BW, albeit not significantly different from level ground, was -5.0 ± 22.6% and 2.9 ± 37.6% at -3° and -6°, respectively. In contrast, the percentage of NMP due to mass was 29 ± 14.3% on level ground, 18 ± 12.2% at +6°, and 44 ± 17.0% at -6°. In summary, we found that at steeper uphill slopes only, the percentage of NMP due to BW significantly increased. However, the percentage of NMP due to mass was not significantly different at any slopes compared to level ground.

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CHAPTER I

INTRODUCTION

To walk over level ground, the muscles of the legs must generate force to support body weight and generate work to accelerate and redirect the center of mass (COM). These mechanical tasks require a substantial percentage of the overall metabolic energy required to walk (Farley & McMahon, 1992; Grabowski, Farley, & Kram, 2005). Specifically, during the stance phase, the leg muscles contract isometrically to support the weight of the body (Farley & McMahon, 1992; Grabowski et al., 2005; Griffin, Roberts, & Kram, 2003; Griffin, Tolani, & Kram, 1999) and during the step-to-step transition when both legs are on the ground, the leading leg decelerates the body and absorbs work while the trailing leg performs positive work on the COM to redirect and accelerate the body (Franz, Lyddon, & Kram, 2012; Grabowski et al., 2005). Previous studies have examined the independent contributions of body weight support and mass on the metabolic cost of level ground walking (Farley & McMahon, 1992; Grabowski et al., 2005), but none, to our knowledge, have investigated how body weight and mass individually affect the metabolic demands while walking on uphill and downhill slopes. By determining the proportion of the metabolic cost attributable to these mechanical tasks, we can provide insight regarding the relationships between metabolic costs and biomechanics and inform assistive device design for walking over a wide range of slopes. Specifically, by better understanding the metabolic costs attributed to biomechanical tasks we could provide lesser abled individuals, such as the elderly, assistive devices that allow them to decrease their metabolic demands and decrease the impact loads experienced on the joints of the legs during sloped walking.

Cost of Generating Force

Generating force to support body weight has been estimated to comprise 28-33% of the net metabolic cost of walking on level ground (Farley & McMahon, 1992; Grabowski et al., 2005). To determine the metabolic demand required to support body weight, previous studies have used both simulated reduced gravity and added weight, and found that metabolic cost does not decrease or increase in direct proportion to body weight (Farley & McMahon, 1992; Grabowski et al., 2005). Instead, metabolic cost decreases in less than direct proportion with body weight. For example, Grabowski et al. (2005) and Farley & McMahon (1992) found that when body weight was reduced by 75%, net metabolic cost decreased by 21% and 33%, respectively. Moreover, Grabowski et al. (2005) found that adding 25% and 50% of body weight increased the net metabolic cost of walking by 39% and 98%, respectively. If the relationship between added weight and metabolic cost was directly proportional, then generating force to support body weight would equate to 100% of the net metabolic cost of walking. However, estimates of the net metabolic cost of reduced weight indicate that supporting body weight may not be the primary determinant of the metabolic cost of walking on level ground.

The trajectory of the COM during walking is sinusoidal and has been modelled as an inverted pendulum during the single leg stance phase (Mochon & McMahon, 1980). This model assumes that the center of mass is a point mass and that the leg is a massless rigid strut. During single leg support, kinetic energy (KE) and gravitational potential energy (GPE) are nearly equal in magnitude, but out of phase (Cavagna et al., 1963; Gottschall & Kram, 2006; Griffin et al., 1999) such that mechanical energy is conserved and the metabolic cost of body weight support is likely small (Cavagna et al., 1963). Deviations from the optimal mechanical energetic conversion would increase metabolic cost during the stance phase (Farley & McMahon, 1992).

Cost of Center of Mass Work

Performing work on the COM has been estimated to be the primary determinant of the metabolic cost of walking (Donelan et al., 2002). To reiterate, little work is required to move the COM along the pendulum arc during single leg support due to a conservation of mechanical energy. However, transitioning the body's COM velocity from one step to the next does require mechanical work from each leg (Donelan et al., 2002). During the step-to-step transition phase of level ground walking, the leg muscles dissipate and generate work to redirect and accelerate the COM from one arc to the next (Donelan et al., 2002; Farley & McMahon, 1992; Griffin et al., 2003). More specifically, during this phase, negative work is absorbed by the leading leg and positive work is performed by the trailing leg (Donelan et al., 2002). The mechanical energy that is lost during the leading leg's collision with the ground at heel strike must be restored by the trailing leg. Therefore, the mechanical work needed for step-to-step transitions incurs a significant metabolic cost during level ground walking (Donelan et al., 2002). Previous studies have calculated the metabolic cost contribution of mass alone by combining the effects of simulated reduced gravity and added loads (Grabowski et al., 2005; Teunissen et al., 2007). Using this method, Grabowski et al. (2005) found that for level ground walking at 1.25 m/s, 45% of the net metabolic cost was attributed to performing mechanical work to redirect and re-accelerate the COM.

Effects of Slopes on Walking Energetics and Biomechanics

Compared to level ground walking, walking on uphill and downhill slopes is different both biomechanically and metabolically. Thus, the metabolic demands attributed to body weight and mass are likely not the same for sloped walking. Supporting body weight may require a substantially greater percentage of the metabolic cost to walk on uphill compared to downhill slopes. This may be due to the overall increase in GPE and greater changes in KE for uphill compared to level ground walking. According to Gottschall and Kram (2006), more energy must be produced to overcome the force of gravity during uphill compared to level-ground walking. This is achieved by increasing the muscular force produced during the stance phase. Conversely, during downhill walking, energy must be dissipated to maintain a constant speed (Gottschall & Kram, 2006), which leads to an overall decrease in GPE and thereby the necessary muscular force, and lesser changes in KE compared to level ground walking. Therefore, to walk uphill the muscles generate more force to overcome gravity and to walk downhill the muscles generate less force.

During walking on uphill and downhill slopes, the mechanical work performed on the COM changes. Franz, Lyddon, and Kram (2012), calculated the individual leg work performed by the leading and trailing legs during uphill and downhill walking at slopes ranging from -9° to +9°. They found that compared to level ground, walking on uphill and downhill slopes requires greater positive and negative work, respectively (Franz et al., 2012; Minetti et al., 1993). More specifically, compared to level ground, the total individual limb positive work increased by 274% and the corresponding negative work decreased by 93% at steeper uphill slopes of +9°. Furthermore, at steeper downhill slopes of -9°, the magnitude of total individual limb negative work increased by 283% and the corresponding positive work decreased by 84% (Franz et al., 2012). Although these results indicate that more positive and negative work is required for walking on uphill and downhill slopes, the metabolic cost attributed to each task is not clear.

Muscular activity while walking uphill and downhill could also explain the independent contribution of COM work on metabolic cost. Using electromyography (EMG), Lay et al. (2007) analyzed the changes to muscle activity during walking on uphill and downhill slopes of +21° to -21°. They found that, compared to level ground, walking up steeper slopes required greater muscle activity magnitudes from hip, knee, and ankle extensors. Conversely, only the magnitude of knee extensor muscle activations increased at steeper downhill slopes. The muscles that act to extend the hip and ankle joints during sloped walking assist in performing the necessary work to redirect the COM (Franz & Kram, 2012; Lay et al., 2007). Further, uphill walking requires greater concentric muscle contractions (Lay et al., 2007), which are associated with a higher metabolic demand than eccentric muscle contractions (Lastayo et al., 1999). These results imply that the metabolic cost contribution of mass alone may be greater during uphill than downhill walking. However, it is not clear whether the cost of mass requires a greater proportion of the metabolic cost than body weight while walking uphill.

By combining the results of Grabowski et al. (2005) and the evidence from sloped walking studies, we can predict how body weight and mass may affect the metabolic cost of walking. Specifically, while walking on uphill slopes, a greater proportion of the metabolic cost could be due to body weight. Further, while walking downhill, the cost of mass may incur a greater cost than body weight.

The purpose of this study was to determine the metabolic contributions associated with body weight (BW) support and mass during uphill and downhill walking. Our results will allow us to quantify the independent relationships between biomechanical tasks and metabolic costs during uphill and downhill walking. We hypothesized that during uphill walking: (1) the proportion of the net metabolic cost due to BW will be greater than that of level ground walking and (2) the proportion of the net metabolic cost due to mass will be less than that of level ground walking. We hypothesized that during downhill walking, (3) the proportion of the net metabolic cost due to BW will be less than that of level ground walking and (4) the proportion of the net metabolic cost due to mass will be greater than that of level ground walking.

CHAPTER II

METHODS

10 healthy adults [5 male, 5 female; 27.5 ± 6.6 years; 169.8 ± 7.3 cm; 65.4 ± 7.4 kg] volunteered to participate in this study. All participants gave informed consent according to the University of Colorado Human Research Committee approved protocol.

Experimental Design

Our protocol consisted of four general walking conditions: unaltered (UA), with reduced weight using simulated reduced gravity, with added weight, and with added mass alone. Participants walked at each of these conditions on level ground (0°) and different uphill (+3° and +6°) and downhill (-3° and -6°) slopes to assess the metabolic costs, both independently and collectively, associated with body weight and mass.

Participants completed five sessions on separate days. At the start of each session, we took anthropometric measurements of height and weight. Subsequently, all participants performed a standing trial followed by seven walking trials on a dual-belt, force-measuring treadmill under various conditions at five different slopes (0°, +/-3°, +/-6°). At each slope, we implemented the following seven conditions: 1. 100% mass (M) and 100% body weight (BW) (i.e. no alterations), 2. 100% M and 75% BW, 3. 100% M and 50% BW, 4. 125% M and 125% BW, 5. 150% M and 150% BW, 6. 125% M and 100% BW, and 7. 150% M and 100% BW, for a total of 35 trials. We chose to vary weight and mass in increments of 25% so that we could compare our results with previous studies (Farley & McMahon, 1992; Grabowski et al., 2005). Participants walked 1.25 m/s for all walking trials except for uphill at +6°, where participants walked 1 m/s. These speeds ensured that participants utilized primarily aerobic metabolism, indicated by a respiratory exchange ratio less than 1.0. All participants completed trials on five separate days at the same time of day. Each trial was five minutes long with at least five minutes of rest between trials. Additionally, participants performed a maximum of seven trials per day to account for any potential effects of fatigue. The trial order for each session was randomized. During each trial, we measured participants' metabolic rates and ground reaction forces. All participants had prior experience to treadmill walking.

Simulated Reduced Gravity

In order to simulate reduced gravity and thereby decrease body weight, we used a vertical cable suspension system (Grabowski et al., 2005; Teunissen et al., 2007) that was attached to an overhead rolling trolley (Fig. 1). This apparatus applies a nearly constant upward force on the participant via a modified climbing harness and long segments (2.39 m) of rubber tubing. Nylon straps attached the harness to a lightweight frame that was suspended above the participant. This frame was attached to a floating pulley that was suspended from a low friction, rolling trolley mounted from the ceiling. In order to adjust the upward force applied to each participant, the floating pulley was attached with a nylon cord to segments of rubber tubing that were stretched via a hand-operated winch. Finally, we used a force transducer (Omegadyne, Sunbury, OH) with a sampling frequency of 1000 Hz located at the terminal end of the nylon cord and overhead frame to measure the upward force applied. The low-friction trolley was designed to move horizontally with the subject as they walked and so that any fore-aft forces applied to the subject were negligible. This adaption of the vertical cable suspension system simulates reduced gravity on the COM. However, the appendages still experience Earth's gravity. The metabolic contribution due to body weight was calculated for each subject using the slope of the linear regression equation of percent net metabolic power relative to percent reduced BW.

$$BW\ Cost = \left(1 - \left(\frac{50\%\ BW}{UA}\right)\right) * 2$$

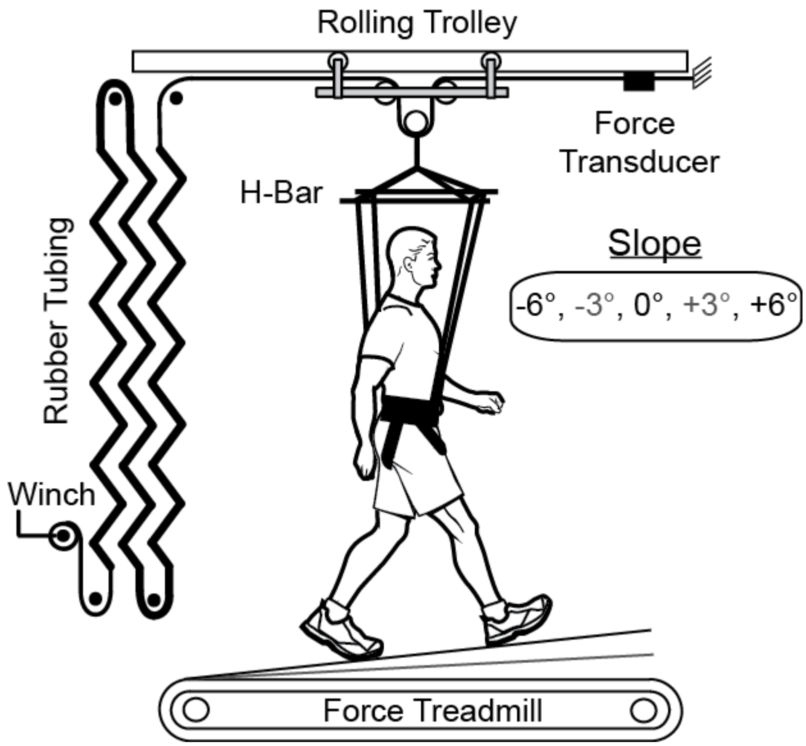

Figure 1. Vertical cable suspension system to simulate reduced gravity. This apparatus, similar to that described in Grabowski et al. (2005), applied a nearly constant upward force on the COM via a modified climbing harness held in suspension by an H-shaped bar. The upward force on the COM was modified by stretching long sections of rubber tubing over low-friction pulleys with a hand-cranked winch. The low-friction rolling trolley ensured that only vertical forces were applied to the subject. We measured the magnitude of the upward force with a force transducer positioned in line with the rubber tubing.

Added Weight and Mass

We added weight and mass by attaching flexible lead strips to a padded belt fixed tightly around each participant's torso. Each lead strip was uniform in weight and size and positioned symmetrically about the waist. The added weights were applied near the COM of the participant in order to minimize the movement of the lead strips during walking. Moreover, this apparatus did not impede the participant's motion and did not interfere with arm swing.

Added Mass Alone

By combining added weight and simulated reduced gravity, we isolated the effects of added mass alone (Grabowski et al., 2005; Teunissen et al., 2007). We used simulated reduced gravity to apply an offsetting upward force equal to the added weight on the participant. Thus, participants maintained body weight, but had added mass. In order to calculate the metabolic contribution due to mass for each subject, we determined the ratio of the percent change in net metabolic power between percent added weight compared to UA and percent added mass alone compared to unaltered (UA) walking at every slope.

$$Mass\ Cost = \frac{(\%\ Added\ Mass - UA)}{(\%\ Added\ BW - UA)}$$

Measurements and Analysis

We measured ground reaction forces at 1000 Hz using a 3-D force-measuring treadmill (Bertec Corporation, Columbus, OH) for 30 seconds at minutes 3 and 4 of each 5 minute trial. Then, the ground reaction forces were filtered with a 4th order Butterworth low pass filter using a custom software program (Matlab, Mathworks, Natick, MA). Subsequently, we set a minimum vertical force threshold value of 20 N to determine the instance of force application. This value was used to find the indices of touchdown and toe-off. By averaging these two indices, we were able to determine the mean BW for each trial. We then compared the mean BW and the output of the force transducer to verify the incremental changes in weight and mass. Rates of oxygen consumption and carbon dioxide production were measured using indirect calorimetry (ParvoMedics TrueOne 2400, Sandy, UT). Additionally, we calculated the average steady-state metabolic power (W) from minutes 3-5 of each trial using a standard equation (Brockway, 1987). Net metabolic power was then determined by subtracting the metabolic power for standing from gross metabolic power. A trial length of five minutes was used to achieve steady-state metabolic rates. A comparison of the metabolic data across conditions allowed us to isolate the individual contributions of each condition to the net metabolic power of walking.

Statistical Analyses

Two pairwise t-tests were used to analyze and compare the percentage of net metabolic power due to BW and mass for each participant between slopes. Statistical significance was accepted at $p < 0.05$. All statistical analyses were conducted using RStudio (RStudio, Inc. v3.2.3, Boston, MA).

CHAPTER III

RESULTS

Unaltered

In general, average net metabolic power (NMP) for subjects walking UA increased at steeper uphill slopes and decreased at steeper downhill slopes (Fig. 2). Average NMP was 2.73 ± 0.29 W/kg on level ground (Fig. 2A), increased to 4.52 ± 0.29 W/kg at +3° and 5.23 ± 0.32 W/kg at +6° (Fig. 2B & C), and decreased to 1.66 ± 0.17 W/kg at -3°, and 1.54 ± 0.29 W/kg at -6° (Fig. 2D & E). All values are reported as means ± standard deviations or percent change ± standard deviations from UA at each specified slope.

Reduced Weight

Using the kinetic data that we collected during each trial, we determined that, across all slopes, BW was reduced by 27 ± 3.4% and 51 ± 3.1%. Additionally, the output from the force transducer indicated that we applied a nearly constant (average force fluctuation per stride was 2.3 ± 1.8%) upward force to each subject.

When we reduced body weight using simulated reduced gravity, there were no changes in average NMP for the 25% and 50% reduced BW conditions compared to UA on level ground (Fig. 2A). However, NMP decreased significantly in less than direct proportion to BW at both uphill slopes. Specifically, during the 50% reduced BW condition, NMP decreased by 32 ± 11.1% at +3° (Fig. 2B) and 39 ± 10.5% at +6° (Fig. 2C). Similar to level ground, there were no changes in NMP for 25% and 50% reduced BW compared to UA at -3° (Fig. 2D) ($p = 0.71$ and 0.68, respectively) and -6° (Fig. 2E) ($p = 0.05$ and 0.89, respectively).

Added Weight and Mass

When we increased weight using loading, NMP was greater than UA and increased in more than direct proportion to added weight at all slopes (Fig. 2). On level ground (Fig. 2A), NMP for 125% BW and 150% BW were 45 ± 18.5% and 120 ± 40.0% greater than UA, respectively ($p<0.001$). At +3° (Fig. 2B), NMP increased by 38 ± 10.9% and 94 ± 27.0% when we added 25% and 50% BW, respectively, compared to UA. Similarly, at +6° (Fig. 2C), NMP increased by 35 ± 10.7% and 88 ± 21.9% when we added 25% and 50% BW, respectively, compared to UA ($p<0.001$). Finally, at -3° (Fig. 2D) NMP increased by 65 ± 25.5% when we added 25% BW and by 164 ± 48.1% when we added 50% BW compared to UA. At -6° (Fig. 2E), NMP increased by 61 ± 26.8% for 125% BW and 157% for 150 ± 78.1% BW compared to UA ($p<0.001$).

Added Mass

Overall, NMP increased when we added 50% mass alone at all slopes compared to UA (Fig. 2). However, we only observed a change in NMP with 25% added mass compared to UA during both downhill slope conditions. On level ground (Fig. 2A), adding 50% mass alone resulted in a 35 ± 20.3% increase in NMP from UA ($p<0.001$). At +3° NMP increased by 22 ± 14.8% (Fig. 2B) and at +6° NMP increased by 17 ± 11.9% with 50% added mass compared to UA (Fig. 2C), respectively ($p=0.001$). At -3°, NMP increased for both 25% and 50% added mass by 26 ± 22.9% and 55 ±21.4%, respectively, compared to UA (Fig. 2D) ($p<0.05$). Similarly, at -6° (Fig. 2E), NMP increased by 21 ± 21.2% and 63 ± 25.1% for 25% and 50% added mass, respectively, compared to UA ($p<0.05$).

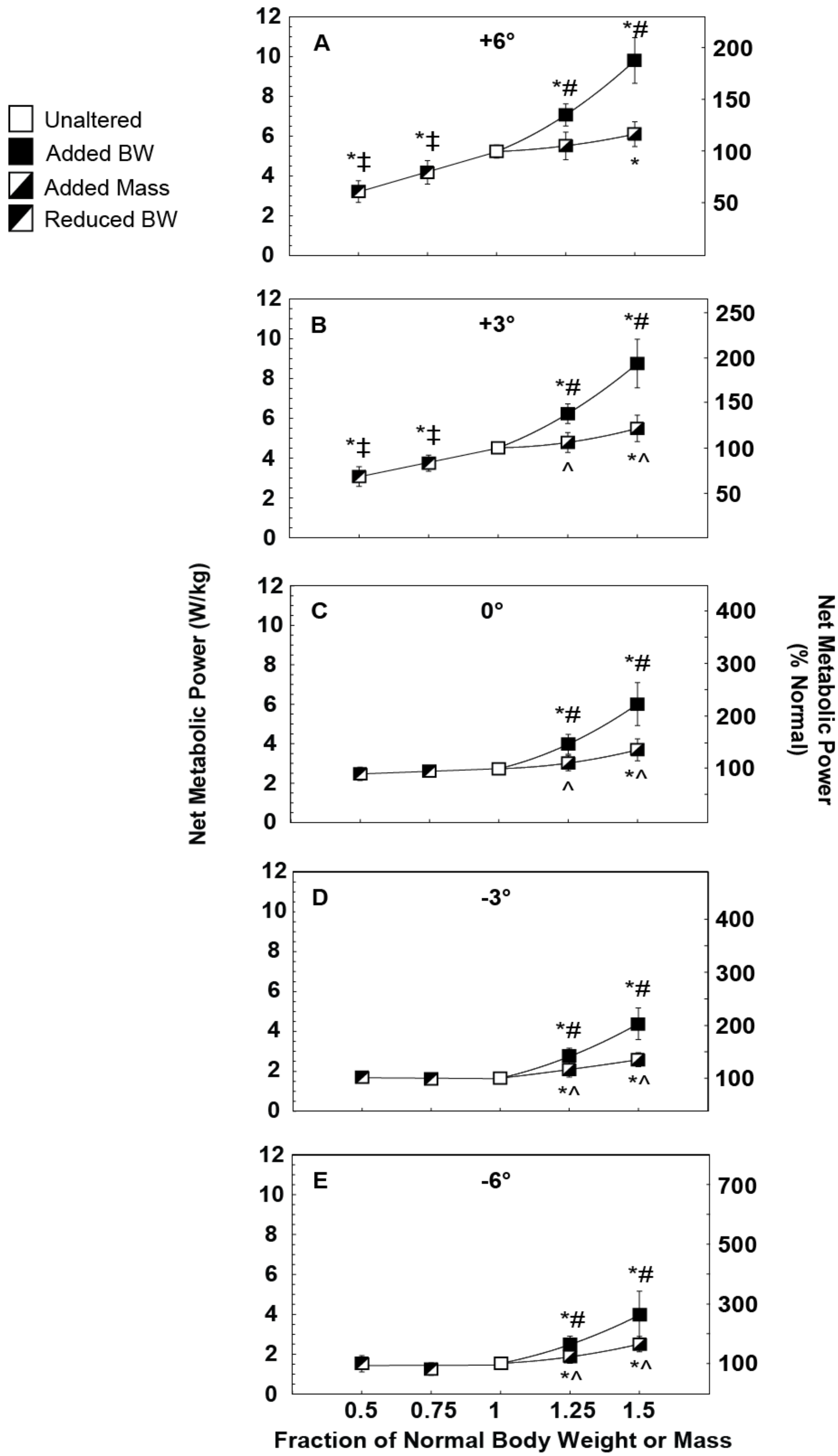
Unaltered
Added BW
Added Mass
Reduced BW
A
+6°
B
+3°
C
0°
D
-3°
E
-6°
Net Metabolic Power (W/kg)
Net Metabolic Power (% Normal)
0.5
0.75
1
1.25
1.5
Fraction of Normal Body Weight or Mass

Figure 2. Average (± S.D.) net metabolic power (W/kg) for reduced BW ◪, added weight ■, and added mass alone ◩ at +6° (A), +3° (B), 0° (C), -3° (D), and -6° (E). Reducing BW decreased NMP from UA for both uphill slopes. Adding weight resulted in an increase in NMP across all slopes compared to UA. Similarly, adding 50% mass alone resulted in an increase in NMP across all slopes compared to UA. * $p<0.05$ vs UA, # $p<0.05$ between added BW conditions, ^ $p<0.05$ between added mass conditions, ‡ $p<0.05$ between reduced BW conditions.

Metabolic Cost Contribution of BW and Mass

The percentage of the NMP due to BW increased at steeper uphill slopes and decreased at steeper downhill slopes compared to level ground (Fig. 3). More specifically, the cost of BW increased from 19% on level ground up to 64% at +3° and 77% at +6° ($p<0.001$); Whereas the cost of BW was ~0% at -3° and -6°. In contrast, we did not find any significant changes in the percentage of the NMP due to mass at any of the uphill ($p = 0.92$) and downhill ($p = 0.91$) slopes compared to level ground. The percentage of the NMP due to mass was 29% on level ground, 23% at +3°, 18% at +6°, 36% at -3° and 44% at -6°.

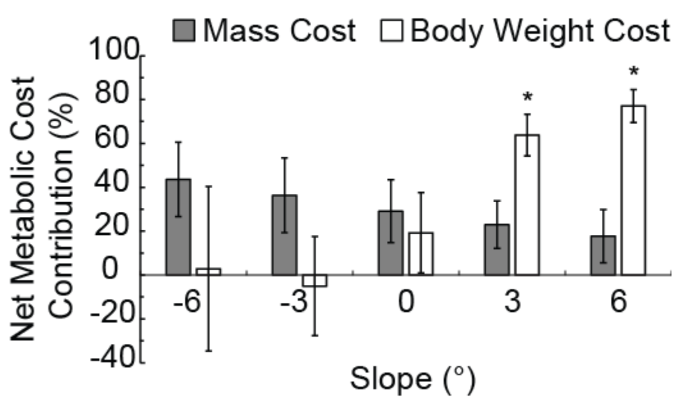

Figure 3. Average ± S.D. percentage of net metabolic power for weight (white) and mass (gray) at each slope (°). The percentage of net metabolic power due to BW was 64 ± 9.4% at +3° and 77 ± 7.5% at +6° compared to level ground. The cost of BW at -3° and -6° conditions were -5.0 ± 22.6% and 2.9 ± 37.6%, respectively. The percentage of net metabolic power due to mass was 29 ± 14.3 % on level ground, 18 ± 12.2% at a +6° incline and 44 ± 17.0% at a -6° decline. * $p<0.05$ vs BW cost on other slopes

CHAPTER IV

DISCUSSION

In the present study, we found, in accordance with our first hypothesis, that walking on uphill slopes required a greater percentage of the net metabolic power due to BW compared to walking on level ground. However, we reject all remaining hypotheses as we did not observe any significant differences in the percentage of the net metabolic power due to BW during downhill walking or the net metabolic cost contribution due to mass at either uphill or downhill slopes compared to level ground.

Cost of BW

We calculated the metabolic cost due to BW from the slope of the linear regression equation for percentage NMP relative to percentage reduced BW (Fig. 2). Contrary to previous studies that estimated BW support to require approximately 28% of the overall net metabolic power (Farley & McMahon, 1992; Grabowski et al., 2005), we found that supporting BW required approximately 19% of the overall net metabolic power for level ground walking. However, our results likely underestimated this cost compared to results from these prior studies. More specifically, although our calculations were similar, we based the slope of the linear regression on UA, 25% reduced BW, and 50% reduced BW; whereas Grabowski and colleagues (2005) also included 75% reduced BW in their calculation. By using the data from 75% reduced BW in Grabowski et al., we estimated the percentage net metabolic power due to BW support on level ground and found that the cost of BW is approximately 32% of the net metabolic power for walking. As hypothesized, the cost of BW increased at steeper uphill slopes. However, we did not observe a significant change in the net metabolic power due to BW for both downhill slopes. The change in the cost of BW for different slopes is likely due to the amount of muscular force necessary to overcome gravity. When walking in simulated reduced gravity, less muscular force is required to produce the necessary gravitational potential energy (GPE) needed for each step (Gottschall & Kram, 2006). To walk uphill, GPE must be increased and, thus, more muscular force is required. The opposite effect is observed during downhill walking.

Surprisingly, the percentage of net metabolic power due to BW was near 0% for both downhill slopes. This could be due to three potential factors. First, while walking downhill at -3° and -6° during the 50% reduced BW condition, subjects adopted a 3.0 ± 3.7% and 4.6 ± 3.9% longer stride length, respectively. According to Donelan et al. (2002), walking with a longer stride length requires significant mechanical work and, thus incurs a substantial metabolic cost. However, previous studies have shown that one of the typical gait strategies that humans adapt while walking downhill includes decreasing stride length (Leroux et al., 2002; Sun et al., 1996). The increased stride length may have been influenced in part by the simulated reduced gravity condition. In a parabolic flight study, Cavagna et al. (2000) observed an increase in stride length for subjects walking at speeds faster than 1 m/s while experiencing 0.4 BW Therefore, the participants in the present study may have adopted a slightly longer stride length while walking under simulated reduced gravity. Moreover, stride length could have also been longer due to the simulated reduced gravity apparatus. The apparatus reduces weight on the body but not on the swinging limbs. Therefore, subjects may have altered their stride characteristics while experiencing simulated reduced gravity. Second, these surprising results may also be caused by a mismatch in GPE and KE fluctuations. During downhill walking, the change in GPE decreases in proportion to the gravitational force, but KE during the downhill reduced gravity conditions may remain unchanged from the downhill UA condition due to the forward velocity of the COM (Farley & McMahon, 1992; Margaria, 1976). Therefore, more mechanical work must be generated by the muscles to make up for this ineffective exchange of mechanical energy. Finally, downhill walking requires greater eccentric muscle contractions that, as previously reported by Lastayo et al. (1999), are associated with a lower metabolic cost than concentric muscle contractions. Therefore, the metabolic cost due to BW that we observed may have been a result of changes to stride characteristics, a mismatch of GPE and KE, and/or greater eccentric muscle contractions.

Cost of Mass

By determining the ratio of the percentage change in NMP between percentage added weight compared to UA and percentage added mass alone compared to UA at every slope we calculated the percentage NMP due to mass on level ground to be ~30%. Again, this value is lower than the cost contribution calculated by Grabowski et al. of ~45%. However, the methodology that we used was similar. Therefore, the reason for this discrepancy is less clear. It is possible that the rolling trolley we used in our study was not frictionless, which could provide a small horizontal assistive force (Grabowski et al., 2005). This would mitigate a portion of the metabolic cost needed to propel the COM forward (Chang et al., 2001; Gottschall & Kram, 2006), thereby decreasing the metabolic cost and decreasing the percentage of the cost due to mass.

We did not observe a significant change in the net metabolic cost contribution due to mass at any uphill or downhill slopes compared to 0°. However, as expected, the percentage of NMP required to walk uphill with added mass alone was approximately 2.5-3x greater than it was for downhill walking. This could simply be the result of changing proportions. In other words, although the net metabolic power for downhill walking with added mass alone was much less than uphill walking, the proportion of the net metabolic power for downhill walking was predominantly due to mass because the cost of BW was ~0%. Similarly, the cost due to BW increased at steeper uphill slopes, thereby decreasing the proportion of the net metabolic power due to mass. However, it is important to note that there are other tasks, such as swinging the limbs, balance, and ventilation, that contribute to the net metabolic cost of walking and it is not clear how these other tasks affect the metabolic cost on different slopes.

Cost of Weight and Mass

When we added weight and mass, net metabolic power increased significantly from UA. This indicates that weight and mass contribute substantially to the net metabolic cost of walking; however the magnitude of these contributions change based on the slope. On level ground, load carrying is attributed to a higher demand on the muscles to support body weight during the stance phase. Additionally, more positive and negative work is necessary to redirect and accelerate the COM (Grabowski et al., 2005). These results are consistent with previous studies that applied loads to subjects while walking (Grabowski et al., 2005; Griffin et al., 2003). Moreover, during uphill walking, more muscular force is required to overcome the force of gravity (Gottschall & Kram, 2006) and less muscular force is presumably required to walk downhill. Further, hip and ankle extensor muscle activity, which is associated with performing the necessary work to redirect the COM, increases during uphill walking (Lay et al., 2007). Taken together, this evidence explains how adding weight and mass increases the metabolic cost of walking.

Our study may be limited by several factors. First, although we simulated reduced gravity on the COM, we were unable to simulate reduced gravity on the swinging limbs. This may have inflated the metabolic cost that we observed during the reduced BW conditions. Second, we did not control for stride length or stride frequency. Instead, we allowed subjects to select their own stride kinematics. On one hand, this is advantageous because self-selected stride characteristics minimize metabolic costs (Cavanagh & Kram, 1985). However, during the 50% reduced BW conditions, subjects in the present study altered their stride characteristics to adapt to downhill walking. Further, walking downhill may have forced the participants to emphasize balance over minimizing metabolic costs. Hunter et al. (2010) assessed the metabolic cost of walking downhill at -3°, -6°, and -9° using self-selected and energetically optimal gait patterns. They found, compared to level ground walking, that when subjects walked downhill at -6° and -9°, their metabolic rate decreased by an additional 16% while using the energetically optimal gait instead of their preferred gait. The authors determined that subjects placed a greater emphasis on ensuring stability rather than minimizing metabolic costs (Hunter et al., 2010). These results indicate that balance may provide a greater contribution to the metabolic cost of walking downhill. Finally, the overhead trolley used for our simulated reduced gravity apparatus may not have been frictionless, which could have provided a small assistive/opposing force that would have influenced the metabolic cost of the task.

Future studies should evaluate how the cost of BW and mass during level and sloped walking change with speed and more extreme slopes. Additionally, more research is needed to determine how these metabolic cost contributions change with varying stride characteristics. Finally, the remaining contributors to the metabolic cost of walking, specifically balance, need to be quantified on uphill and downhill slopes.

The results from the present study could be used to design assistive devices for walking over a diverse range of slopes. More specifically, these potential devices could reduce impact loads experienced at the joints while reducing or increasing the metabolic demand of walking. This application of our results could be used to benefit individuals rehabilitating from injuries that limit their ability to walk, lesser-abled individuals with a limited capacity to walk, or elderly populations that need to reduce the impact loads placed on their joints or modify the metabolic demand of walking to fit their needs. Additionally, these results could be used properly tune a powered ankle prostheses such as the BIOM. Based on our findings, when negotiating uphill slopes, for instance, it would be more important to tune these devices by increasing the power in the vertical direction as opposed to the horizontal direction. This configuration would generate an adequate amount of force in order to store the necessary GPE for walking uphill.

In summary, we found that at steeper uphill slopes, the contribution of the net metabolic cost due to BW increases. In contrast, the net metabolic cost due to BW did not change between level ground and downhill slopes. Similarly, the net metabolic cost contribution due to mass was not significantly different at any slope compared to level ground.

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