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Independent metabolic costs of supporting body weight and accelerating body mass during walking

Alena Grabowski, Claire T. Farley, and Rodger Kram

Department of Integrative Physiology, University of Colorado, Boulder, Colorado

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Grabowski, Alena, Claire T. Farley, and Rodger Kram. Independent metabolic costs of supporting body weight and accelerating body mass during walking. *J Appl Physiol* 98: 579–583, 2005; doi:10.1152/japplphysiol.00734.2004.—The metabolic cost of walking is determined by many mechanical tasks, but the individual contribution of each task remains unclear. We hypothesized that the force generated to support body weight and the work performed to redirect and accelerate body mass each individually incur a significant metabolic cost during normal walking. To test our hypothesis, we measured changes in metabolic rate in response to combinations of simulated reduced gravity and added loading. We found that reducing body weight by simulating reduced gravity modestly decreased net metabolic rate. By calculating the metabolic cost per Newton of reduced body weight, we deduced that generating force to support body weight comprises ~28% of the metabolic cost of normal walking. Similar to previous loading studies, we found that adding both weight and mass increased net metabolic rate in more than direct proportion to load. However, when we added mass alone by using a combination of simulated reduced gravity and added load, net metabolic rate increased about one-half as much as when we added both weight and mass. By calculating the cost per kilogram of added mass, we deduced that the work performed on the center of mass comprises ~45% of the metabolic cost of normal walking. Our findings support the hypothesis that force and work each incur a significant metabolic cost. Specifically, the cost of performing work to redirect and accelerate the center of mass is almost twice as great as the cost of generating force to support body weight.

locomotion; biomechanics; reduced gravity; load carriage

THE METABOLIC COST OF WALKING is determined by mechanical tasks such as generating force to support body weight, performing work to redirect and accelerate the center of mass from step to step, swinging the limbs, and maintaining stability (4, 7–15, 17, 19, 21, 22). Previous studies have examined the metabolic cost attributable to combinations of these mechanical tasks, but it remains unclear how much each task individually contributes to the overall metabolic cost of walking. We sought to establish the separate metabolic costs of generating force to support body weight and of performing work to redirect and accelerate the center of mass during walking by independently manipulating weight and mass.

Cost of generating force. The inverted pendulum model provides a basis for understanding how force generation to support body weight contributes to the cost of walking. This model portrays center of mass motion during human walking when only one foot is in contact with the ground. During this single-stance phase, the body's center of mass follows an arclike trajectory, whereas the stance leg acts as a rigid support (3). This model suggests that little mechanical work must be performed on the center of mass during the single-stance phase of human walking because kinetic and gravitational potential energy fluctuations are nearly equal in magnitude and 180° out of phase (4). However, a nearly isometric muscular force must be generated to prevent the leg from collapsing and to support the weight of the body. This muscular force generation presumably incurs a significant metabolic cost.

Simulated reduced gravity acutely reduces body weight and has therefore been utilized to determine the metabolic cost of generating muscular force to support the weight of the body during walking (11, 15). When humans walk in simulated reduced gravity, their net metabolic cost does not decrease in direct proportion to body weight. For example, when Farley and McMahon (11) reduced body weight by 75%, the net metabolic cost of walking decreased by only 33%. This relatively small decrease in metabolic cost cannot be explained by a mismatch of kinetic and gravitational potential energy that would compromise inverted pendulum energy exchange (15). These findings suggest that generating force to support body weight does contribute to the metabolic cost of walking but that there are additional mechanical tasks that incur more substantial metabolic costs.

Cost of performing work. Changes of the center of mass energy during step-to-step transitions can be estimated by using a simple collision-based model of walking (8). This model describes the amount of energy lost to each collision between the foot and the ground at heel-strike. Thus the model describes the work performed on the center of mass to redirect it upward and forward between steps. Donelan et al. (8) combined results from this collision-based model along with experimental evidence and found that the mechanical work needed for step-to-step transitions exacts a significant metabolic cost that comprises almost one-half of the cost of normal walking.

Previous studies that simultaneously changed both weight and mass by loading subjects have been unable to separate the metabolic costs of generating force to support body weight and of performing work to redirect and accelerate body mass. When humans walk while carrying moderate to heavy loads, their net metabolic rate increases in more than direct proportion with added load (13, 16, 22). Griffin et al. (13) calculated that the magnitude and rate of muscle force generation during loaded walking can account for >85% of the increase in net metabolic rate in response to added loads. Yet the cost of performing work on the center of mass could also account for much of the metabolic cost of carrying loads (13).

Address for reprint requests and other correspondence: A. Grabowski, Dept. of Integrative Physiology, Univ. of Colorado, 354 UCB, Boulder, CO 80309-0354 (E-mail: alena.grabowski@colorado.edu).

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The purpose of the present study was to quantify the individual contributions of generating force to support body weight and of performing work to redirect and accelerate the center of mass on the metabolic cost of walking. We independently changed body weight and mass by using combinations of simulated reduced gravity and loading while measuring metabolic rate. We hypothesized that the force generated to support body weight and the work needed to redirect and accelerate body mass each incur a significant independent metabolic cost during normal walking.

METHODS

Ten healthy adults volunteered to participate in the study [5 male, 5 female, mean body mass 68.65 kg (SD 8.1), mean body weight 673.5 N (SD 79.3)]. All subjects gave informed consent, according to the University of Colorado Human Research Committee approved protocol.

Experimental design. Our experimental design allowed us to determine the separate and combined metabolic costs attributable to supporting body weight and performing work on the center of mass. First, we kept body mass constant while varying body weight by simulating reduced gravity. To simulate reduced gravity, we applied an upward force on the body. This procedure reduced the amount of force that was supported by the legs. Subsequently, we varied both weight and mass by loading the subjects. Finally, we kept weight constant while varying total mass using combinations of simulated reduced gravity and loading.

Each subject performed an unloaded standing trial and then eight different walking trials on a motorized treadmill at 1.25 m/s. Subjects walked normally [1.0 body weight (BW) and 1.0 mass (M)] at three levels of simulated reduced gravity (0.75BW, 0.50BW, and 0.25BW at 1.0M) and with two added loads (1.25BW and 1.25M, 1.50BW and 1.50M). Then, by combining simulated reduced gravity and loading (1.0BW and 1.25M, 1.0BW and 1.50M), subjects walked at normal body weight with added mass.

We implemented a specific trial order to minimize harness and simulated reduced gravity apparatus adjustments, thus reducing the total duration of the experiment. Trial order was as follows: normal, 0.75BW and 1.0M, 0.50BW and 1.0M, 0.25BW and 1.0M, 1.25BW and 1.25M, 1.0BW and 1.25M, 1.50BW and 1.50M, and 1.0BW and 1.50M. We chose 25% increments of weight and mass so that our results could be compared with previous studies. Each trial was 7 min long with at least a 5-min rest between walking trials.

Subjects demonstrate almost immediate habituation to normal treadmill walking and habituate to simulated reduced gravity walking within 1 min of treadmill walking (7). Therefore, it was not necessary to accommodate subjects to treadmill walking before testing. The rest period and the low-to-moderate intensity of activity during trials were adequate to prevent the effects of fatigue.

Reduced gravity. We reduced body weight by applying a nearly constant upward force near the whole body center of mass (Fig. 1), as previously described by Griffin et al. (15). Each subject wore a modified climbing harness around the waist and pelvis that was attached to the reduced gravity apparatus. A force transducer (Omegadyne, Sunbury, OH) measured the upward force applied to the subject via long segments of rubber tubing. We stretched the rubber tubing with a hand-cranked winch and thereby regulated the force applied to the subject. At each reduced gravity setting, a near-constant force was exerted on the subject (varied less than ±0.06 g; g = 9.81 m/s^2) due to the low stiffness and large stretch of the rubber tubing. The reduced-gravity apparatus applied negligible forward or backward force on subjects because a low-friction rolling trolley moved with subjects as they walked.

The apparatus simulated reduced gravity on the center of mass, but not on the swinging limbs. Donelan and Kram have previously demonstrated that, when gravity is reduced to 25% of normal, preferred stride frequency changes by only 8% (7). This small change in stride frequency implies that swing mechanics do not change substantially with simulated reduced gravity. Our apparatus design was also advantageous for our study because the weight, mass, and moment of inertia of the swinging legs remained unchanged. Thus we could manipulate and examine the independent effects of body weight and mass without altering leg-swing mechanics.

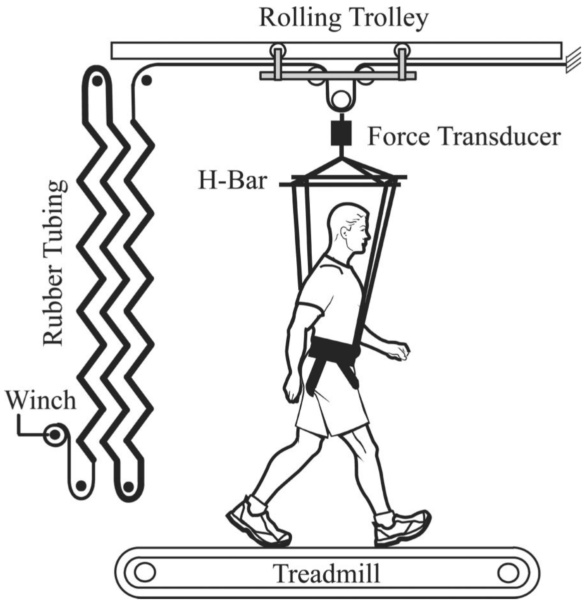

Fig. 1. Reduced gravity apparatus applied a nearly constant upward force on the body via a modified climbing harness held in suspension by an H-shaped bar. We adjusted the upward force by stretching long sections of rubber tubing over low-friction pulleys with a hand-cranked winch. A low-friction rolling trolley ensured that only vertical forces were applied to the subject. We measured the magnitude of reduced gravity with a force transducer that was in line with the rubber tubing.

Added load. We added loads by securing strips of lead symmetrically to a wide, well-padded belt that wrapped tightly around the subject's hips near the whole body center of mass. This placement minimized load movement relative to the center of mass, allowed an upright posture, did not load the shoulders or back, and did not interfere with arm swing.

Metabolic energy. To determine the metabolic cost of walking, we measured the rates of oxygen consumption and carbon dioxide production using an open-circuit respirometry system (Physio-Dyne Instrument, Quogue, NY). We averaged oxygen consumption and carbon dioxide production for *minutes 4–6* of each trial and calculated metabolic rates using the Brockway equation (2). Previous studies have determined that standing metabolic rate is not influenced by reduced gravity (11) or added load (14), so we subtracted the unloaded standing metabolic rate from each walking metabolic rate to determine the net metabolic rate for each trial. We confirmed that subjects consumed metabolic energy supplied primarily by oxidative metabolism, as indicated by respiratory exchange ratios that were <1.0 during all trials.

Statistical measurements. We performed three single-factor repeated-measures ANOVA statistical analyses using SuperANOVA (Abacus Concepts, 1989): one test for reduced body weight, one for added load, and one for added mass. When the ANOVA test, with condition as the factor, indicated significant differences among means, we used a posteriori contrasts (comparison of means) to test differences between specific means using a sequential Bonferroni correction to account for multiple comparisons ($P < 0.007$). Statistical comparisons were made on the raw data. After statistical analysis, the metabolic rate data were normalized to unloaded body mass and expressed as a ratio of the metabolic rate during unloaded walking.

RESULTS

Normal. The average gross metabolic rate during unloaded standing was 1.55 W/kg (SE 0.06). During normal walking at 1.25 m/s, subjects' average gross metabolic rate was 4.19 W/kg (SE 0.11), and thus their net metabolic rate was 2.64 W/kg (SE 0.10).

Reduced gravity. Net metabolic rate decreased moderately, but in less than direct proportion to body weight as we simulated reduced gravity (Fig. 2). When subjects walked with a 25% reduction in body weight, the decrease in net metabolic rate was not significant. However, when we reduced body weight by 50 and 75%, net metabolic rate decreased significantly by 11.0 (SE 4.9) and 21.0% (SE 4.9), respectively.

Added weight and mass. Net metabolic rate increased significantly and in more than direct proportion to added weight and mass as we loaded subjects (Fig. 3). When subjects walked with added loads equal to 25 and 50% of their body weight and mass, net metabolic rate increased by 39.0 (SE 5.6) and 98.0% (SE 13.0), respectively.

Added mass. Net metabolic rate increased when we added mass while keeping weight constant (Fig. 3). The increase in net metabolic rate due to added mass alone was only about one-half as much as the increase in net metabolic rate due to added weight and mass. When subjects walked with added loads equal to 25 and 50% of body mass at normal body weight, net metabolic rate increased significantly by 18.0 (SE 4.8) and 48.0% (SE 7.5), respectively.

DISCUSSION

We determined the individual contributions of generating force to support body weight and of performing work to redirect and accelerate the center of mass to the metabolic cost of walking by comparing the results from each of our experimental protocols.

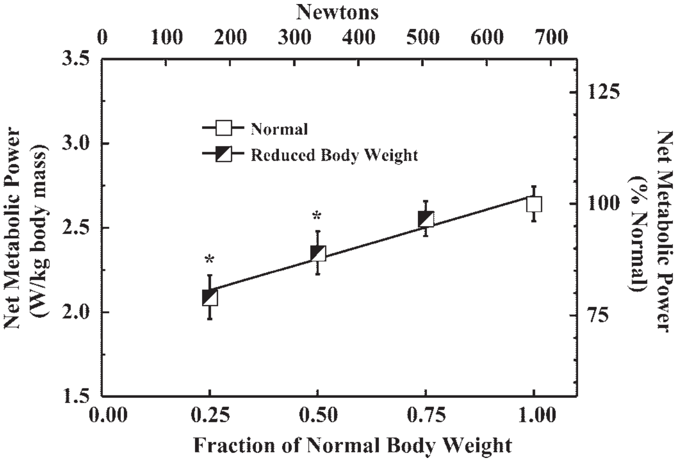

Fig. 2. Net metabolic power for walking normally (open square) and walking in simulated reduced gravity (half-solid squares). The reduction of body weight resulted in a modest linear decrease in net metabolic power that was less than proportional. Net metabolic power decreased by only 21% when we reduced body weight by 75%. Line is a linear least squares regression: W/kg = 0.744·BW + 1.94; BW equals the fraction of normal body weight, $R^2 = 0.26$. Error bars are SE (W/kg). *Net metabolic power was significantly lower at 0.25BW and 0.50BW than at 1.0BW ($F = 19.67$; $P = 0.0009$).

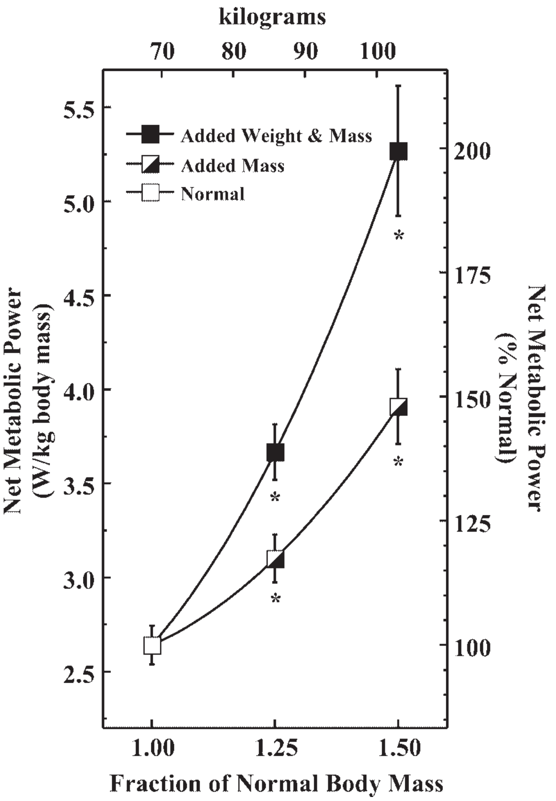

Fig. 3. Net metabolic power (W/kg unloaded body mass) for walking normally (open square), with added mass at normal body weight (half-solid squares), and with added weight and mass (solid squares). Net metabolic power increased by 48% when we added 50% of mass alone via loading and simulated reduced gravity. Net metabolic power nearly doubled when we added 50% of both weight and mass via loading. Lines are second-order least squares regressions. Added mass, W/kg = $2.77 \cdot M^2 - 4.40 \cdot M + 4.27$; M equals the fraction of normal body mass, $R^2 = 0.58$. Added body weight and mass, W/kg = $4.60 \cdot (\text{BW and M})^2 - 6.23 \cdot (\text{BW and M}) + 4.28$; BW and M equals the fraction of normal body weight and mass, $R^2 = 0.72$. Error bars are SE (W/kg). *Significant differences from normal (added weight and mass $F = 79.30$, $P = 0.0001$; added mass alone $F = 65.788$, $P = 0.0006$).

Cost of generating force. We accept our hypothesis that body weight support incurs a significant metabolic cost during walking. As we reduced body weight by 75%, the net metabolic cost of walking at 1.25 m/s decreased by an average of 21% (Fig. 2). By calculating the slope (0.076 W/N) of the linear regression equation from Fig. 2 (W/kg = 0.744·BW + 1.94; BW equals the fraction of normal body weight, $R^2 = 0.26$), we estimate that body weight support comprises 28% of the net metabolic cost of normal walking. We chose a linear fit for our data rather than a curvilinear fit, based on the precedence of Farley and McMahon (11). The R^2 value for a curvilinear fit (0.27) was essentially the same as the R^2 value for a linear fit (0.26).

Our results indicate a smaller metabolic contribution of force generation to support body weight than a previous reduced gravity study (11). Farley and McMahon (11) found that a 75% decrease in body weight reduced the net metabolic cost of walking at 1 m/s by 33%, whereas our results indicate a 21% reduction in cost. This disparity may be a consequence of the different apparatus used to simulate reduced gravity. The apparatus used by Farley and McMahon applied vertical force from a pulley that was fixed to the ceiling. This setup may have inadvertently provided aiding horizontal forces to subjects and thus may have led to an overestimate of the metabolic cost of body weight support. Pulling forward on subjects with a force of 10% body weight can reduce the metabolic cost of walking by ~50% (12). Our simulated reduced gravity apparatus applied vertical force from a low-friction rolling trolley that moved forward and backward with each subject as he or she walked (Fig. 1), thereby preventing the application of horizontal aiding or impeding forces.

Combined cost of generating force and performing work. Our results from the loading trials suggest that force generation and work production both contribute significantly to the net metabolic cost of walking (Fig. 4). Load carrying increases the demands on muscles to support a greater weight during stance and to redirect and accelerate a greater mass during step-to-step transitions. Our results are similar to those of previous loading studies, which have shown that metabolic energy consumption increases in more than direct proportion when subjects carry moderate-to-heavy symmetrical loads while walking (13, 16, 22).

Cost of performing work. We accept our hypothesis that performing work on the center of mass independently incurs a significant metabolic cost during loaded walking. By calculating the ratio of the change in net metabolic cost due to added mass alone to the change in net metabolic cost due to added weight and mass, we determined that the work done to redirect and accelerate mass comprises about one-half of the cost of loaded walking. For example, adding 25% of body mass alone while maintaining body weight increased net metabolic power by 0.46 W/kg unloaded body mass, and adding 25% of both weight and mass increased net metabolic power by 1.03 W/kg. The ratio of the change in costs reveals that 45% of the increased metabolic cost of walking can be attributed to the work done to redirect and accelerate the center of mass under this load. Adding 50% of body mass alone resulted in a ratio of 48%. Our methods may be useful for estimating the energetic cost of human locomotion during lunar and Martian exploration, because these explorations involve carrying substantial mass (i.e., life-support systems) in a reduced gravity environment.

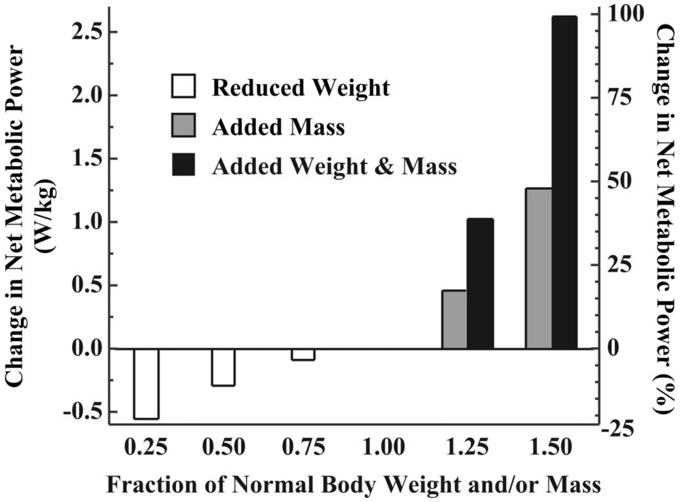

Fig. 4. Changes in net metabolic power for walking in simulated reduced gravity (open bars), with added mass at normal body weight (shaded bars), and with added mass and weight (solid bars).

To determine the cost of performing work on the center of mass during normal walking, we calculated the initial slope of the added mass-only curve. We used the average body mass of 68.85 kg and the regression equation to determine that adding 1 kg of body mass increases net metabolic rate by 1.18 W (Figs. 3 and 4). From this calculation, we estimate that the work done to redirect and accelerate normal body mass comprises 45% of the net metabolic cost of normal walking.

Two other independent lines of evidence concur with our estimate that about one-half of the net metabolic cost of normal walking is due to performing work on the center of mass. First, Donelan et al. (10) measured that 0.3 W/kg of mechanical power are needed to replace the energy lost during step-to-step transitions during walking at 1.25 m/s. Assuming 25% efficiency (18), the metabolic cost of step-to-step transitions is 1.2 W/kg. Our net cost of normal walking was 2.64 W/kg, and thus ~45% of the cost of walking may be attributed to step-to-step transitions. Second, Gottschall and Kram (12) provided an external aiding horizontal force at the waist of human walkers and measured the reduction in metabolic cost. When an optimal force was applied, subjects generated close to zero propulsive force on the ground, and their net metabolic cost of walking decreased by 47% (12). This result suggests that the work performed to propel the center of mass forward constitutes nearly one-half of the net metabolic cost of normal walking.

Three aspects of our experimental design deserve further consideration. First, we simulated reduced gravity on the center of mass but not on the swinging limbs. This design was advantageous because we did not alter the weight, mass, or moment of inertia of the swinging legs. Second, we did not control stride frequency while simulating reduced gravity or loading, and stride frequency changes may influence net metabolic rate. However, in a previous study on the kinematics of walking in simulated reduced gravity, Donelan and Kram (7) found that subjects walked with only 8% higher stride frequencies in 75% reduced gravity than in normal gravity. Such small changes in stride frequency result in a negligible change in net metabolic cost (20). We allowed our subjects to choose their own stride frequency as they walked under different conditions because humans naturally choose stride characteristics that minimize metabolic cost (5, 6, 20). We, therefore, avoided potential increases in the cost of swinging the legs that may have occurred if we had enforced a specific stride frequency. Third, although we could reduce weight to estimate its cost, we could not increase weight without increasing mass, because we could not simulate increased gravity. It is not known whether the changes in metabolic cost due to reduced weight are equal in magnitude to the changes in metabolic cost due to increased weight.

To gain more insight into the mechanical determinants and metabolic cost of walking, some specific future studies are needed. First, simulated hypergravity studies could test whether independently increasing body weight results in equal but opposite changes in metabolic cost compared with simulated reduced gravity. Second, we need to measure the external step-to-step transition work on the center of mass during various loading and unloading experiments. We were not able to measure external step-to-step work with our existing force treadmill, but we could measure this work with a dual-belt force treadmill (1). Third, future studies should address how the percentage of the metabolic cost attributable to each mechanical factor changes with speed and incline.

In summary, we found that the force generated to support body weight and the work performed to redirect and accelerate the center of mass each incur a significant metabolic cost during normal walking. We also found that the cost of performing work is almost twice the cost of generating force.

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GRANTS

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