Effects of independently altering body weight and body mass on the metabolic cost of running

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Summary

The metabolic cost of running is substantial, despite the savings from elastic energy storage and return. Previous studies suggest that generating vertical force to support body weight and horizontal forces to brake and propel body mass are the major determinants of the metabolic cost of running. In the present study, we investigated how independently altering body weight and body mass affects the metabolic cost of running. Based on previous studies, we hypothesized that reducing body weight would decrease metabolic rate proportionally, and adding mass and weight would increase metabolic rate proportionally. Further, because previous studies show that adding mass alone does not affect the forces generated on the ground, we hypothesized that adding mass alone would have no substantial effect on metabolic rate. We manipulated the body weight and body mass of 10 recreational human runners and measured their metabolic rates while they ran at $3 \, m \, s^{-1}$. We reduced weight using a harness system, increased mass and weight using lead worn about the waist, and increased mass alone using a combination of weight support and added load. We found that net metabolic rate decreased in less than direct proportion to reduced body weight, increased in slightly more than direct proportion to added load (added mass and weight), and was not substantially different from normal running with added mass alone. Adding mass alone was not an effective method for determining the metabolic cost attributable to braking/propelling body mass. Runners loaded with mass alone did not generate greater vertical or horizontal impulses and their metabolic costs did not substantially differ from those of normal running. Our results show that generating force to support body weight is the primary determinant of the metabolic cost of running. Extrapolating our reduced weight data to zero weight suggests that supporting body weight comprises at most 74% of the net cost of running. However, 74% is probably an overestimate of the metabolic demand of body weight to support itself because in reduced gravity conditions decrements in horizontal impulse accompanied decrements in vertical impulse.

Key words: biomechanics, reduced gravity, energetics.

Introduction

During level running, the leg muscles must support body weight, brake/propel the center of mass in the fore–aft direction and swing the legs forward. Little work is necessary to overcome air resistive forces (Van Ingen Schenau and Cavanagh, 1990), the net external mechanical work performed on the center of mass is nearly zero (Cavagna et al., 1977) and the legs effectively act like springs that store and return elastic energy within each step (Cavagna et al., 1977; Farley and Ferris, 1998). However, the metabolic cost of running is substantial.

Previous studies suggest that generating force to support body weight is the primary determinant of the metabolic cost of running (Farley and McMahon, 1992; Kram and Taylor, 1990; Taylor et al., 1980). Body weight is specifically defined as the gravitational force acting on the body and is measured in Newtons. A second major determinant of the metabolic cost of running is forward propulsion of body mass (Chang and Kram, 1999). Body mass is independent of gravitational acceleration and is thus measured in kilograms. It seems reasonable that manipulating either body weight or body mass would affect the metabolic cost of running. However, the metabolic effects of independently altering body weight and body mass have not been previously measured in running.

Increasing both body mass and body weight by adding centrally placed loads to running animals nearly proportionally increases their gross metabolic rate (Marsh et al., 2006; Taylor et al., 1980). Farley and McMahon (Farley and McMahon, 1992) used a harness system on human runners to simulate reduced gravity, thereby reducing body weight but not body mass. They found that as body weight was reduced, net metabolic cost decreased proportionally. These results support the idea that the net metabolic cost of running is proportional to body weight. Subsequently, Chang et al. (Chang et al., 2000) manipulated mass alone by adding loads to runners' waists while applying an upward compensatory force. When mass alone was increased, the horizontal and vertical impulses per step barely increased. Impulse is defined as the integral of force with respect to time. Although metabolic cost was not measured, the data from Chang

et al. suggest a primary role for supporting body weight and a minimal role for braking/propelling body mass on the cost of running. In contrast, in an earlier study, Chang and Kram (Chang and Kram, 1999) showed that there is a substantial metabolic cost of forward propulsion in running. They applied external aiding horizontal forces to human runners and found that the gross rate of oxygen consumption decreased by 33%. Assuming a standing rate of oxygen consumption of 5.5 ml kg^{-1} min^{-1}, one can deduce from Chang and Kram's study that forward propulsion comprises about 39% of the overall net metabolic cost of running. Therefore, the independent determinants of the metabolic cost of running remain uncertain.

A recent experiment on the metabolic cost of walking used a novel approach that may help resolve this uncertainty. Grabowski et al. (Grabowski et al., 2005) demonstrated that body weight and body mass each exact a significant metabolic cost during level walking. Similar to Chang et al. (Chang et al., 2000), Grabowski et al. (Grabowski et al., 2005) independently manipulated body weight and mass and found that the metabolic cost of supporting body weight comprises ~28% whereas accelerating body mass comprises ~45% of the overall net metabolic cost of walking. These results differed quantitatively from those of a similar study by Farley and McMahon (Farley and McMahon, 1992). Both studies reported that net metabolic cost decreases as body weight is reduced during level walking. However, the magnitude of this decrement reported by Grabowski et al. was distinctly less than that reported by Farley and McMahon. These differences may be attributed to the slightly different apparatus used in each study. Both studies used a cable to apply a nearly constant upward force to subjects near their center of mass and thus simulated reduced gravity. However, Farley and McMahon passed the cable over a pulley that was fixed to the ceiling, whereas in the study by Grabowski et al., the cable was attached to a rolling trolley. The apparatus used by Farley and McMahon may have unintentionally provided aiding horizontal force on their subjects, which may have led to an overestimation of the metabolic cost of body weight support in both walking and running. Using the same rolling trolley reduced gravity apparatus as Grabowski et al., Bijker (Bijker, 2003) found that gross metabolic rate at a freely chosen running speed decreased by 27% when body weight was reduced by 50%. This decrement equates to a ~32% reduction in net metabolic rate, which is less than the 50% proportional reduction found by Farley and McMahon (Farley and McMahon, 1992).

In summary, it is not clear how supporting body weight and braking/propelling body mass independently affect the metabolic cost of running. Further, there is reason to re-examine the simulated reduced gravity method of Farley and McMahon (Farley and McMahon, 1992). We aimed to resolve these issues by independently manipulating body weight and body mass, and by comparing both the 'fixed pulley' and the 'rolling trolley' methods of simulating reduced gravity. We quantified metabolic rates during normal running and running under several combinations of reduced gravity and loading. Specifically, we reduced only weight, added both mass and weight, and added mass alone. We hypothesized that for running: (1) metabolic rates would be greater with the rolling trolley method compared with the fixed pulley method at equivalent levels of simulated reduced gravity; (2) reducing body weight would decrease metabolic rate proportionally; (3) adding mass and weight would increase metabolic rate proportionally; (4) because Chang et al. (Chang et al., 2000) found that adding mass alone did not change the forces applied to the ground, adding mass alone would have no significant effect on metabolic rate.

Materials and methods
Subjects
Ten trained recreational human runners (6 male, 4 female, age 32±7 years, body mass 63.3±9.8 kg, means ± s.d.) participated in this study. We informed each subject of the purposes, protocol, experimental procedures, and any associated risks and benefits of the study. Each subject gave written consent to participate. The University of Colorado Human Research Committee approved the experiment. Subjects were all experienced treadmill runners and previous studies have shown rapid habituation to the experimental conditions that we used in this study (Donelan and Kram, 2000), so it was not necessary to accommodate subjects before testing.

Overview
Subjects ran on a force-measuring treadmill normally, under simulated reduced gravity (reduced weight), with added mass and weight, and with added mass alone. We measured their rates of oxygen consumption and carbon dioxide production, ground reaction forces (GRFs) and kinematics.

Protocol
Each subject completed a total of 16 trials on two separate days (Table 1). Both days started with an unloaded standing trial and a normal running trial (100% body mass and 100% body weight). Subjects ran at 3.0 m s^{-1} for all of the running trials. On day 1, subjects proceeded with six trials at different levels of simulated reduced gravity: three trials with the fixed pulley method and three trials with the rolling trolley method. On day 2, subjects proceeded with three added mass and weight trials followed by three added mass alone trials. Each trial was 7 min long with several minutes of rest between trials. The rest period combined with the moderate aerobic intensity of the activity were adequate to prevent any effects of fatigue.

Table 1. *Summary of experimental trials*

Trial	Day 1	Day 2
1	Unloaded standing	Unloaded standing
2	100% BM and 100% BW	100% BM and 100% BW
3	100% BM and 75% BW fixed	110% BM and 110% BW
4	100% BM and 50% BW fixed	120% BM and 120% BW
5	100% BM and 25% BW fixed	130% BM and 130% BW
6	100% BM and 25% BW trolley	130% BM and 100% BW
7	100% BM and 50% BW trolley	120% BM and 100% BW
8	100% BM and 75% BW trolley	110% BM and 100% BW

BM, body mass; BW, body weight; fixed, fixed pulley method; trolley, rolling trolley method.

We used this specific trial order to reduce the adjustments to the equipment, reduce the total duration of the experiment and thus make the experiment more comfortable for the subjects. We chose 25% decrements in gravity so that we could compare our results with previous studies (Chang et al., 2000; Farley and McMahon, 1992). We chose 10, 20 and 30% increments in added weight and mass so that we could compare our results with those of Chang et al. (Chang et al., 2000). We also considered that running with loads greater than 30% might be too strenuous and could increase the possibility of fatigue or injury.

Equipment and calculations

Metabolic rate

We measured the rates of oxygen consumption ($\dot{V}_{O_2}$) and carbon dioxide production ($\dot{V}_{CO_2}$) using an open-circuit respirometry system (Physio-Dyne Instrument, Quogue, NY, USA) during all trials. The gas analyzers were calibrated before each test using reference gases. The flow-rate transducer was calibrated using a 3 l syringe (Rudolph Inc., Kansas City, MO, USA). We averaged $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$, expiratory ventilation ($\dot{V}_E$) and respiratory exchange ratios for minutes 4–6 of each trial and calculated metabolic rates (in W kg^{-1}) using the Brockway equation (Brockway, 1987) and body mass. Metabolic rate is always expressed per normal body mass. We determined the net metabolic rate for each trial by subtracting the unloaded standing metabolic rate from the gross metabolic rate values. Previous studies have shown that standing metabolic rate is not influenced by reduced gravity (Farley and McMahon, 1992) or added load (Griffin et al., 2003) and that the delivery of oxygen to tissues that are not involved in exercise changes little from rest to exercise (Ellerby et al., 2005; Poole et al., 1992).

We normalized net metabolic rate by converting it to a percentage of normal (normal body weight and mass) net metabolic rate for running at 3.0 m s^{-1}. This calculation factored out intersubject variability in running economy and allowed us to compare our results with previous studies. We used the unloaded standing and normal running trials performed on the same test day to calculate net and normalized values. Respiratory exchange ratios were less than 1.0 for all subjects and for all trials, which indicates that metabolic energy was supplied primarily by oxidative metabolism.

Force-measuring treadmill

Subjects ran on a custom-made motorized force treadmill that measured vertical and horizontal GRFs (Kram et al., 1998) during all of the trials. At the start of minute 4, we sampled 15 s of force data for each trial at 1000 Hz. We filtered these data with a 4th order low-pass Butterworth filter using a cut-off frequency of 15 Hz and processed the data using a customized Matlab program (Natick, MA, USA) to calculate kinematic and kinetic variables. We calculated peak vertical and horizontal forces, vertical and horizontal impulses (area under the force–time curve), contact time, aerial time, stride frequency and duty factor (ratio of contact time to stride time). Based on the vertical GRF, the Matlab program detected the instant of initial foot–ground contact and the instant of toe-off. From the difference in these time values, the program calculated foot–ground contact time. Then, the program calculated stride
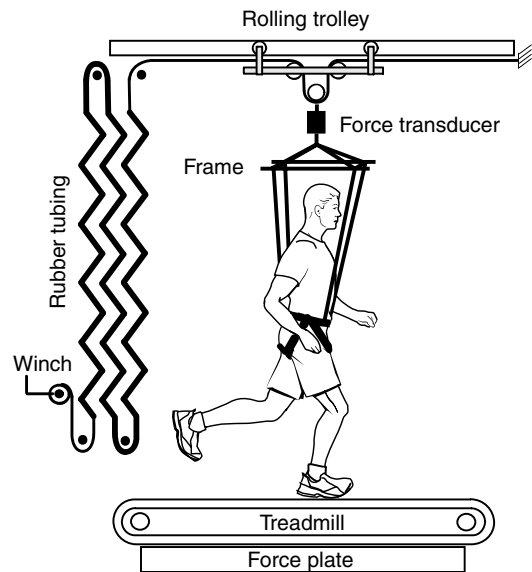

Fig. 1. Reduced gravity apparatus.

times, and hence stride frequencies, from the time difference between subsequent ipsilateral foot–ground contacts.

Reduced gravity

We simulated reduced gravity for the three rolling trolley trials by applying a nearly constant upward force to the pelvis of subjects via a modified climbing harness (Fig. 1), as previously described by Grabowski et al. (Grabowski et al., 2005). Four nylon straps attached the climbing harness to a lightweight frame that hung above the subject's head. The frame hung from a low friction rolling trolley by a cable. The rolling trolley insured that no significant forward or backward forces were applied to the subjects. However, to allow for comparison with Farley and McMahon's data (Farley and McMahon, 1992), we intentionally fixed the trolley at one horizontal position for the three fixed pulley simulated reduced gravity trials. We adjusted the upward force applied to each subject by stretching one or two long segments of rubber tubing with a hand-cranked winch. A force transducer (Omegadyne, Sunbury, OH, USA) located between the lightweight frame and the trolley, measured the applied upward force.

Our apparatus simulated reduced gravity on the entire body center of mass, but not on the swinging limbs. This apparatus was 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. Other methods of simulating reduced gravity such as underwater and parabolic flight running exhibit comparable GRFs and contact times at 3 m s^{-1} (Chang et al., 2000; Newman, 1996; Newman et al., 1994). Overall, the suspension apparatus was the most practical and reliable method to attain our research goals. For comparisons of the advantages and disadvantages of different methods for simulating reduced gravity, see Davis and Cavanagh (Davis and Cavanagh, 1993), and Donelan and Kram (Donelan and Kram, 1997).

Added mass and weight

We added both mass and weight by firmly attaching flexible lead strips (3 mm thick) symmetrically to a padded belt that wrapped tightly around the subject's waist. This attachment minimized movement of the lead relative to the body's center of mass, did not load the subject's shoulders or back, and did not interfere with arm swing. The total loads reported include the mass and weight of the padded belt.

Added mass alone

We combined loading and simulated reduced gravity to increase mass alone. In these trials, the reduced gravity apparatus with a rolling trolley applied a compensatory upward force that was equal to the added weight. We could thereby keep body weight constant and isolate the effects of added mass alone.

Statistics

Although our graphs depict normalized values, all statistics were performed on raw, non-normalized data. We compared each subject's metabolic rate and biomechanical variables across conditions using repeated measures ANOVAs with Tukey's HSD follow-up tests when warranted ($P<0.05$). We used paired comparisons to analyze metabolic rates for the fixed pulley and rolling trolley trials at the same level of reduced gravity.

Results

Overall, we found that net metabolic rate decreased in less than direct proportion to reduced body weight, increased in slightly more than direct proportion to added load (added mass and weight), and was not substantially different from normal running with added mass alone.

Normal

Subjects' average metabolic rate during unloaded standing was 1.87 ± 0.07 W kg^{-1} (mean ± s.e.m.). Normal running required a gross metabolic rate of 11.61 ± 0.19 W kg^{-1}. As a result, the mean net metabolic rate was 9.74 ± 0.20 W kg^{-1}. Values are means of days 1 and 2.

Reduced weight

Net metabolic rate decreased significantly in all simulated reduced gravity conditions for both the fixed pulley and rolling trolley methods (Fig. 2, Table 2). Although reducing gravity with the fixed pulley method appeared to decrease net metabolic
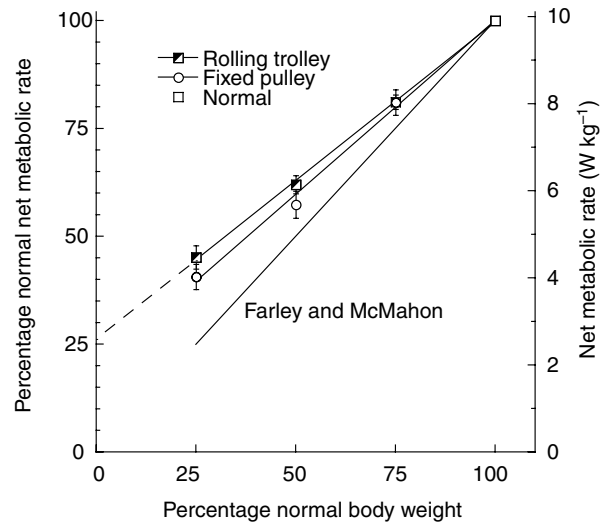

Fig. 2. Net metabolic rate for running as a percentage of normal body weight from the rolling trolley method (half-solid squares), the fixed pulley method (open circles), the Farley and McMahon (Farley and McMahon, 1992) data (solid line), and normal running (open square). Net metabolic rate decreased substantially when we reduced body weight. The dashed line indicates an extrapolation to zero weight. Lines are linear least squares regressions. Rolling trolley: (%NNMR) = $0.73 \times$ %BW + 26.18; R^2=0.88; and fixed pulley: %NNMR = $0.81 \times$ %BW + 19.36; R^2=0.84; where %NNMR is the percentage of normal net metabolic rate and %BW is the percentage of normal body weight. Error bars are s.e.m. Within the rolling trolley and fixed pulley methods, metabolic rates were all significantly different from each other ($P<0.0001$). However, at a given percentage of body weight, there was no significant difference between rolling and fixed trolley methods ($P>0.08$). Statistics were calculated on absolute values.

rate slightly more than with the rolling trolley method, there were no statistical differences between the two methods at equivalent levels of weight support ($P>0.08$). Simulating reduced gravity with the rolling trolley method reduced net metabolic rate significantly, but in less than direct proportion to body weight (Fig. 2, Table 2). When subjects ran at 75% of normal body weight, net metabolic rate decreased by 19±1.7% compared with normal running. At 50% and 25% of normal body weight, net metabolic rate decreased by 38±2.1% and 55±2.7%, respectively. These decreases in metabolic rate are substantially smaller than those found by Farley and McMahon (Farley and McMahon, 1992). Our mean metabolic rates were

Table 2. *Normalized net metabolic rate under different reduced gravity conditions*

Body weight (% normal)	Rolling trolley	Fixed pulley	Farley and McMahon
100	100	100	100
75	81 (1.7)	81 (2.9)	75
50	62 (2.1)	57 (3.1)	50
25	45 (2.7)	41 (2.9)	28

Data are mean values (±s.e.m.) for normalized net metabolic rate (% normal); data in the right-hand column are from Farley and McMahon (Farley and McMahon, 1992). Within the rolling trolley and fixed pulley experiments, metabolic rates were all significantly different from each other ($P<0.0001$). However, at a given percentage of body weight, there was no significant difference between the rolling trolley and fixed pulley methods ($P>0.08$). Statistics were calculated on absolute values.
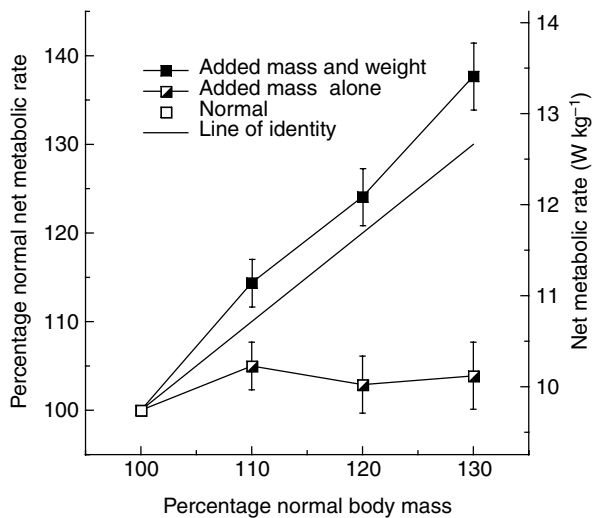
Fig. 3. Net metabolic rate for running with added mass and weight (solid squares), with added mass at normal body weight (half-solid squares), and with normal weight and mass (open square). Net metabolic rate increased slightly more than in direct proportion to added mass and weight. Net metabolic rate increased only slightly when we added mass alone. Error bars are s.e.m. (W kg^{-1}). Metabolic rates at all levels of added mass and weight were significantly different from each other and from normal ($P<0.004$). For the added mass alone trials, the only significant difference was between 110% added mass and normal ($P=0.005$). Statistics were calculated on absolute values.
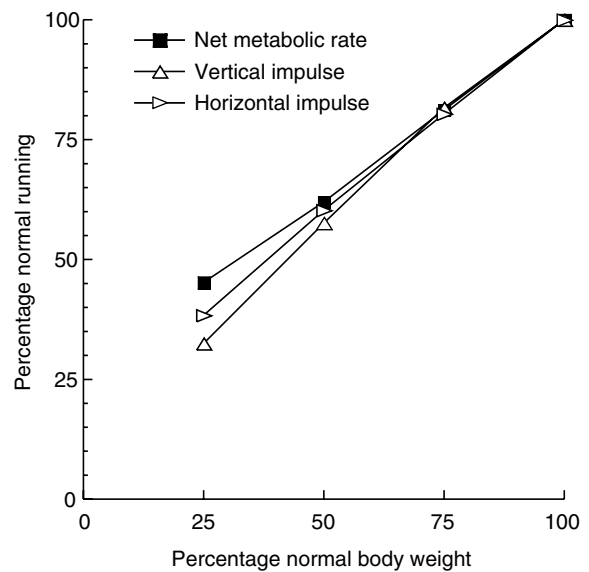

Fig. 4. Normalized net metabolic rate (solid squares), vertical impulse (open triangles pointing up) and horizontal impulse (open triangles pointing right) for running with reduced body weight. Body weight support resulted in significant and substantial linear decreases with nearly similar slopes for all variables. At 25% body weight, the vertical impulse data diverged slightly from net metabolic rate.

more than 3 s.e.m. greater than Farley and McMahon's mean metabolic rates. Further, the slope of the linear regression from our data is outside the 95% confidence interval for the slope of the linear regression from Farley and McMahon's data.

Added mass and weight

Net metabolic rate increased significantly and in slightly more than direct proportion to added load (Fig. 3, Table 3). When subjects ran at 110% of normal body mass and weight, net metabolic rate increased by 14±2.7% compared with normal running. At 120% and 130% of normal body mass and weight, net metabolic rate increased by 24±3.2% and 38±3.8%, respectively.

Added mass alone

There were only small differences in net metabolic rate between the added mass alone trials and normal running (Fig. 3, Table 3). When subjects ran at 110% of normal body mass, net metabolic rate increased by only 5±1.9% compared with normal running ($P=0.005$). This increase in metabolic rate was only about one-third as large as the increase in metabolic rate due to adding 10% of normal mass and weight. At 120% and 130% of normal body mass, there were no significant differences in net metabolic rate compared with normal running. At all levels of loading, adding both mass and weight incurred a significantly greater change in net metabolic rate than adding mass alone.

Ground reaction forces

Active peak vertical GRF, vertical impulse, peak horizontal braking and propulsive GRFs, and horizontal impulse values all decreased significantly and linearly in less than proportion with weight support (Fig. 4, Table 4) compared with normal running. For example, at 25% body weight, the active peak vertical GRF, vertical impulse, peak horizontal braking and propulsive GRFs, and horizontal impulse were 40%, 33%, 47%, 42% and 39% of normal running, respectively. GRFs and impulses increased significantly and linearly in slightly less than proportion with added loads of mass and weight compared with normal running (Fig. 5, Table 4). For example, at 130% body mass and weight, active peak vertical GRF, vertical impulse, peak horizontal braking and propulsive GRFs, and horizontal impulse were 112%, 125%, 119%, 118% and 128% of normal running, respectively. When we added mass alone, the active peak vertical GRF and vertical impulse did not change significantly, except for a slight increase in vertical impulse with 20% of added mass alone (Fig. 6, Table 4). Added mass alone resulted

Table 3. *Normalized net metabolic rate under different loading conditions*

Body mass (% normal)	Mass and weight	Mass alone
100	100	100
110	114 (2.7)	105 (1.9)
120	124 (3.2)	103 (1.7)
130	138 (3.8)	104 (3.0)

Data are mean values (±s.e.m.) for normalized net metabolic rate (% normal). Metabolic rates at all levels of added mass and weight were significantly different from each other and from normal ($P<0.004$). For the added mass alone trials, the only significant difference was between 110% and normal ($P=0.005$). Statistics were calculated on absolute values.

Table 4. *Vertical and horizontal peak ground reaction forces and impulses under different running conditions*

%BM/%BW	Peak vertical GRF (N)	Vertical impulse (N s)	Peak horizontal braking GRF (N)	Peak horizontal propulsive GRF (N)	Horizontal impulse (N s)
100/100	1481 (11)	208 (1)	155 (5)	152 (4)	10.9 (0.1)
100/75	1235 (11)*	170 (1)*	129 (4)*	127 (3)*	8.8 (0.1)*
100/50	944 (11)*	120 (1)*	94 (4)*	103 (3)*	6.6 (0.1)*
100/25	589 (13)*	68 (1)*	73 (4)*	64 (3)*	4.2 (0.1)*
110/110	1512 (10)	222 (1)*	162 (5)*	160 (4)*	11.8 (0.1)*
120/120	1589 (10)*	243 (1)*	174 (4)*	173 (4)*	13.0 (0.1)*
130/130	1663 (11)*	260 (2)*	185 (6)*	180 (5)*	13.9 (0.2)*
110/100	1447 (10)	212 (1)	159 (4)	153 (4)	11.3 (0.1)*
120/100	1466 (10)	217 (1)*	166 (4)*	157 (3)*	11.8 (0.1)*
130/100	1443 (9)	215 (1)	167 (4)*	156 (3)	11.7 (0.1)*

BM, body mass; BW, body weight; GRF, ground reaction force. Data are mean values (±s.e.m.). Asterisks indicate a significant difference from normal body weight and mass running ($P<0.05$).

in increases in both horizontal GRFs and horizontal impulse. For example, with 30% of added mass alone, peak horizontal braking GRF increased to 108% and horizontal impulse increased to 107% of normal running. Our biomechanical results were nearly the same as those of Chang et al. (Chang et al., 2000).

Discussion

Method of reduced gravity

Contrary to our first hypothesis, we did not find statistically significant differences in net metabolic rate between the fixed pulley and rolling trolley methods at any level of simulated reduced gravity. However, the fixed pulley method incurred the same or numerically less metabolic cost than the rolling trolley

method (Fig. 2, Table 2). Unfortunately, we were not able to precisely replicate Farley and McMahon's apparatus (Farley and McMahon, 1992). The cable between the subject and the pulley that applied the upward force was much shorter in length for their study than for our study (personal communication, C. T. Farley). Due to the shorter cable length, their fixed pulley system had a greater potential to inadvertently apply a larger aiding horizontal force onto the subjects if they lagged behind the pulley. With a fixed pulley system, and especially when simulating low levels of gravity, a slight backward drift in horizontal position of the subject on the treadmill relative to the pulley could result in an unintended horizontal forward pulling force. For example, when simulating 25% of normal gravity, an angle of just 8 degrees between the upward pulling cable and vertical would result in a forward pull of 10% body weight. This forward pull alone could produce a substantial reduction in the
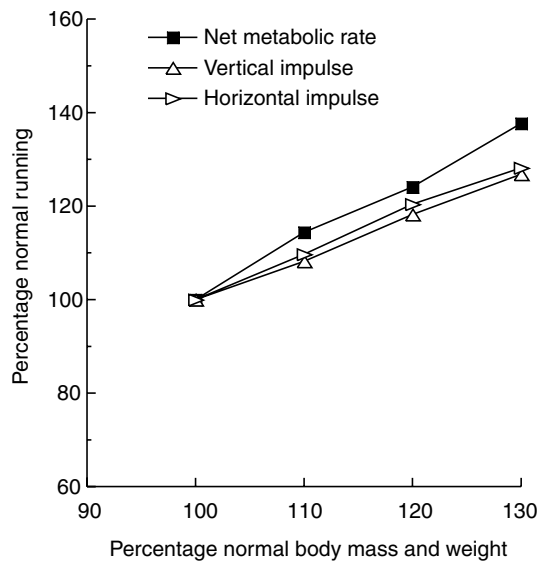

Fig. 5. Normalized net metabolic rate (solid squares), vertical impulse (open triangles pointing up) and horizontal impulse (open triangles pointing right) for running with added mass and weight. Net metabolic rate increased significantly and more than proportionally with added mass and weight, while both horizontal and vertical impulses increased significantly and slightly less than proportionally with added mass and weight.
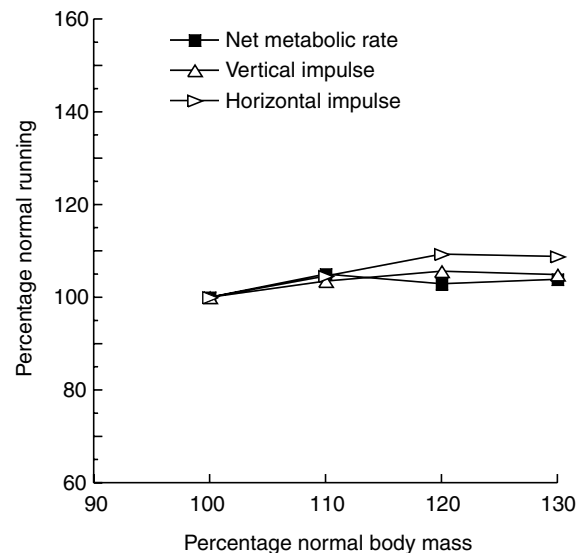

Fig. 6. Normalized net metabolic rate (solid squares), vertical impulse (open triangles pointing up) and horizontal impulse (open triangles pointing right) for running with added mass alone. Net metabolic rate, vertical impulse and horizontal impulse increased only slightly when we added mass alone.

metabolic cost of running (Chang and Kram, 1999). Our fixed pulley was approximately 1.5 m above the subject's center of mass and probably applied a smaller aiding horizontal force than the apparatus of Farley and McMahon (Farley and McMahon, 1992). It is also possible that subjects might have actually run ahead of the fixed pulley in the Farley and McMahon study, but it is our experience that runners are adept at finding the conditions that require the least effort. To avoid any effects of unintended horizontal force application, we advocate use of the rolling trolley method for future research. For the remainder of this article, we will only discuss results obtained with the rolling trolley method.

Metabolic effects of reduced weight

With regard to our second hypothesis, running with reduced body weight decreased metabolic rate substantially, but less than proportionally. When running at 50% and 25% of normal body weight, net metabolic rate decreased by 38% and 55% compared with normal running, respectively. Our reductions in net metabolic rate are substantially less than the nearly proportional 50% and 72% reductions reported by Farley and McMahon (Farley and McMahon, 1992). As mentioned, methodological issues concerning the reduced gravity apparatus might explain this difference. Farley and McMahon's small number of subjects (N=4) may also explain some of the differences between their results and ours. Despite the quantitative differences, Farley and McMahon's general conclusion, that weight support is the major determinant of the metabolic cost of running, remains true.

By extrapolating the linear regression equation shown in Fig. 2 (%NNMR=0.73×%BW+26.18; where %NNMR is percentage normal net metabolic rate and %BW is percentage body weight) to zero body weight, we estimate that the net metabolic cost of body weight support during running comprises 74% of the total net metabolic cost of running. This estimate corroborates the idea that muscular force generation acting in opposition to gravity is the primary determinant of the metabolic cost of running (Kram and Taylor, 1990; Taylor, 1994). Extrapolating our metabolic rate data to the zero-weight intercept was a necessary but non-ideal procedure. The 95% confidence intervals for the slope of the linear regression indicate a y-intercept value of 26.18±6.08%. Therefore, the net metabolic cost of body weight support during running is probably within a range of 67.76–79.88%. Additionally, we calculated net metabolic rate by subtracting standing metabolic rate. If we had used a different baseline value, e.g. metabolic rate while lying horizontally, this may have slightly altered the zero-weight intercept. The use of a specific baseline value for the calculation of net metabolic rate remains controversial (Poole et al., 1992) and deserves further investigation.

Further, our metabolic data closely parallel our force data (Fig. 4). Vertical and horizontal impulses show substantial linear decreases that are similar to the decreases in net metabolic rate. At 25% of normal body weight, the impulse data diverge slightly from net metabolic rate, suggesting that other factors may be playing a larger role in determining the metabolic cost of running than at normal body weight running.

Metabolic effects of added mass and weight

Net metabolic rate increased in slightly more than proportion to added mass and weight (Fig. 3, Table 3), generally supporting our third hypothesis. Our results are consistent with several studies indicating that the relative increase in net metabolic rate is slightly greater than the relative increase in mass and weight (Bilzon et al., 2001; Epstein et al., 1987; Marsh et al., 2006; Taylor et al., 1980). In our added mass and weight trials, metabolic cost per kilogram and cost per Newton exceeded the metabolic costs for normal mass and weight running. For example, a 10% increase in body mass and weight increased net metabolic rate by 14%. If we use this value to infer the metabolic cost of normal running, we would conclude that the metabolic cost of normal running was 40% more than it really was. If we used the values for the 20% and 30% added loading conditions, the overestimates would be 20% and 27%, respectively. It seems that there is a metabolic penalty paid for loading because GRFs and impulses increased proportionally with added loads (Fig. 5, Table 4). This penalty may result from greater muscle activation to stabilize these loads (either trunk and/or leg musculature), recruitment of less economical motor units or an impaired ability to re-utilize elastic energy. Thorstensson (Thorstensson, 1986) hypothesized that the addition of an extra load could lead to greater elastic energy utilization, but our results do not support this idea.

Metabolic effects of added mass alone

We accept our fourth hypothesis, that adding mass alone would have no significant effect on metabolic rate (Fig. 3, Table 3). When we increased mass alone and kept weight at the normal level, there was little increase in net metabolic rate compared with normal running. The slight increase in net metabolic rate for the 10% added mass alone trial is probably the result of a small resonance problem between some of the runners and the reduced gravity apparatus. This resonance, which appeared only during a few of the 10% added mass alone trials, caused the frame to rotate or bounce turbulently. This disturbance may have slightly elevated the metabolic cost of running.

Because we found no substantial effect of adding mass alone on the net metabolic rate during running, one might conclude that the metabolic cost of running is almost entirely dependent on body weight support. However, Chang and Kram (Chang and Kram, 1999) found that braking/propelling body mass comprised approximately 39% of the net metabolic cost of running. In parallel with the decrease in metabolic rate, Chang and Kram measured substantial changes in horizontal impulse due to an aiding applied horizontal force, while the average vertical GRF did not change by more than 1.6%. The metabolically cheap braking impulses increased with the amount of aiding horizontal force, but the expensive propulsive impulses decreased relatively more, which resulted in an overall decrease in net metabolic rate. In the added mass alone conditions, our force data showed only slight increases in horizontal impulse (Fig. 6, Table 4). Thus, our data do not contradict the conclusions of Chang and Kram. Rather, adding mass alone was simply not an effective method for determining the metabolic cost of braking/propelling body mass. Additionally, the applied horizontal force could have biased the
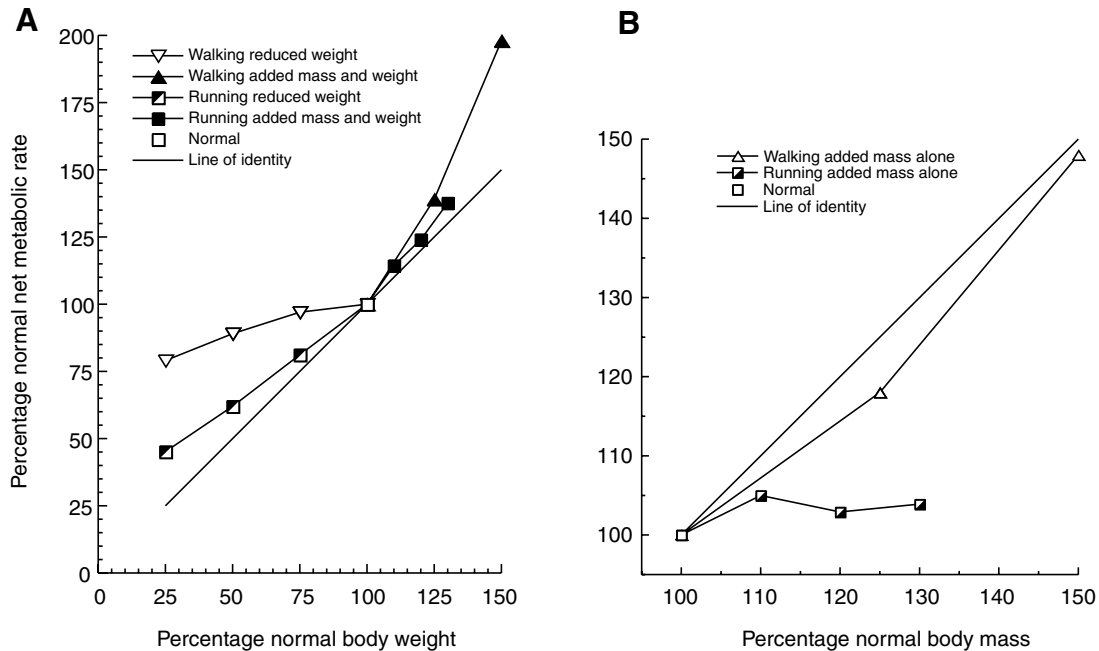
Fig. 7. (A) Net metabolic rate (% normal) for walking with reduced body weight (open triangles), walking with added mass and weight (solid triangles), running with reduced body weight (half-solid squares), running with added mass and weight (solid squares), and walking and running normally (open square). Net metabolic rate decreased only modestly in reduced weight walking, but substantially in reduced weight running (21% *vs* 55% at 25% body weight, respectively). Net metabolic rate increased more than proportionally with added mass and weight in walking, and nearly proportionally with added mass and weight in running. (B) Net metabolic rate (% normal) for walking with added mass alone (open triangles), running with added mass alone (half-solid squares), and walking and running normally (open square). Net metabolic rate increased substantially with added mass in walking, but did not substantially increase with added mass in running. Data for walking were obtained from Grabowski et al. (Grabowski et al., 2005).

muscles that support body weight toward more eccentric actions, which are known to be more economical.

Force data

Our GRF results (Table 4) were essentially the same as those of Chang et al. (Chang et al., 2000). We found that in simulated reduced gravity, vertical and horizontal impulses decreased substantially (Fig. 4), and that with added mass and weight, vertical and horizontal impulses increased nearly proportionally (Fig. 5). Adding mass alone resulted in only a slight increase in horizontal impulse (Fig. 6). The impulse patterns were, when normalized, remarkably similar to the normalized net metabolic rate patterns (Figs 4–6). Impulses and metabolic cost are tightly coupled. This coupling supports the idea that the metabolic cost of running is largely a function of the muscular force produced both to support body weight and to propel the body mass forward (Kram and Taylor, 1990; Taylor, 1994). The vertical GRFs are much greater than horizontal GRFs. However, horizontal GRFs can have a considerable effect on metabolic cost because they orient the resultant GRF, which determines the required joint moments and, ultimately, muscle forces.

Metabolic cost of running

We sought to determine how supporting body weight and braking/propelling body mass independently affect the metabolic cost of running by manipulating body weight and body mass. Extrapolating our results to zero body weight

implies that the net metabolic cost of supporting body weight is about 74% of the total cost of running. Chang and Kram (Chang and Kram, 1999) found that the net metabolic cost of braking/propelling body mass is about 39% of the total cost of running. Finally, the net metabolic cost of swinging the legs appears to be about 10–12% of the total cost of running (Moed and Kram, 2005). The metabolic costs attributable to these three mechanical tasks sum to approximately 125%. Though this estimate improves upon the previous idea that the metabolic cost allocated for body weight support alone was equal to 100% of the metabolic cost of running (Farley and McMahon, 1992), our estimated 125% sum is obviously not realistic. However, the interactive effects of reduced gravity on GRF patterns may explain the 25% overestimate.

The results of Chang et al. (Chang et al., 2000) and our results (Table 4) show that changing gravity alone has an effect on both vertical and horizontal GRFs. Chang et al. reasoned that, in response to the changes in vertical GRF, the horizontal GRF must be proportionally adjusted to keep the angle of the resultant GRF aligned with the long axis of the leg. Humans and many other running animals probably use this mechanism of force alignment (Alexander, 1991; Biewener, 1989; Biewener, 1990; Full et al., 1991) to minimize net muscle moments about the joints. Fig. 4 implies that the vertical and horizontal impulse lines would have non-zero intercepts. Hypothetically, residual vertical forces would be needed at zero weight to reverse the downward movement of the center of mass and this redirection force would presumably incur some metabolic cost. It is

Table 5. *Contact time, aerial time, stride frequency and duty factor under different running conditions*

%BM/%BW	Contact time per step (s)	Aerial time per step (s)	Stride frequency (Hz)	Duty factor
100/100	0.257 (0.002)	0.081 (0.002)	1.48 (0.003)	0.38 (0.01)
100/75	0.257 (0.001)	0.096 (0.002)	1.42 (0.003)*	0.37 (0.02)
100/50	0.229 (0.002)*	0.141 (0.003)*	1.35 (0.004)*	0.31 (0.01)*
100/25	0.203 (0.002)*	0.197 (0.004)*	1.26 (0.005)*	0.26 (0.01)*
110/110	0.261 (0.001)	0.074 (0.002)	1.50 (0.002)	0.39 (0.01)
120/120	0.275 (0.001)	0.059 (0.002)	1.51 (0.002)	0.41 (0.01)
130/130	0.281 (0.001)*	0.049 (0.002)*	1.52 (0.003)*	0.43 (0.01)*
110/100	0.272 (0.001)	0.074 (0.002)	1.45 (0.003)*	0.39 (0.01)
120/100	0.269 (0.001)	0.082 (0.002)	1.43 (0.002)*	0.38 (0.01)
130/100	0.271 (0.001)	0.081 (0.002)	1.43 (0.003)*	0.39 (0.01)

BM, body mass; BW, body weight. Data are mean values (±s.e.m.). Asterisks indicate a significant difference from normal body weight and mass running ($P<0.05$).

difficult to ascribe meaning to the zero-weight intercept of the horizontal impulse lines, but clearly our intentional reductions in vertical force inadvertently reduced the braking/propulsive forces. Thus, the extrapolation of our metabolic rate data to zero weight (Fig. 2) reflects both the reduced need to support body weight and some reduced horizontal impulse generation. This reasoning leads to the conclusion that 74% probably overestimates the cost attributable to weight support alone.

Running vs walking

There are important comparative differences between our running results (Fig. 7A,B) and previous walking results (Grabowski et al., 2005). The first notable difference is the greater metabolic influence of body weight support in running (Fig. 7A). Supporting body weight comprises a much greater percentage of the net metabolic cost of running than walking (74% *vs* 28%). In running, the stance limb posture is more flexed than in walking, implying a smaller limb mechanical advantage and greater knee extensor impulse during running (Biewener et al., 2004). This difference in limb posture probably contributes to a greater metabolic cost of supporting weight for human running than for walking. Adding mass alone has a large effect on the metabolic cost in walking, but not in running (Fig. 7B). Walking requires that the muscles perform a substantial amount of mechanical work with every step to replace the energy lost at heel-strike (collision cost). This lost energy is restored by the trailing leg as it extends to redirect and re-establish the velocity of the center of mass (Donelan et al., 2002a; Donelan et al., 2002b). In running, the legs act like springs that store and return elastic energy (Farley and Ferris, 1998). Our data for the added mass alone conditions suggest that in running there are no substantial collision costs.

Further considerations and future research

Our estimation of the metabolic cost of generating force to support body weight did not consider the rate of force generation. Kram and Taylor (Kram and Taylor, 1990) proposed that $1/t_c$ (where t_c is the foot–ground contact time) is an indicator of the rate of force generation. Running in simulated reduced gravity entails briefer foot–ground contact times (see Table 5). Thus, with weight support, the reduction in the vertical GRF probably reduced metabolic rate; however, the greater rate of force generation may have attenuated the reduction in metabolic rate. Yet, changes in the rate of force generation ($1/t_c$) were modest when compared with the 50% and 75% reductions in vertical force required and thus may not have greatly affected the reduction in metabolic rate.

In our experimental trials, we did not control stride frequency because humans naturally choose stride characteristics that minimize metabolic cost (Cavanagh and Kram, 1985; Cavanagh and Williams, 1982). Enforcing a fixed stride frequency might have increased the metabolic cost attributable to leg swing. Stride frequency during loading trials increased less than 5%, while during simulated reduced gravity trials stride frequency decreased less than 15% (Table 5). Cavanagh and Williams (Cavanagh and Williams, 1982) indicate that enforcing a 15% greater stride frequency would only incur ~6% increase in oxygen consumption rate. We therefore believe that the freely chosen changes in stride frequency did not greatly influence changes in metabolic cost.

Our reduced gravity apparatus showed turbulent behavior during some of the 10% added mass alone trials. This behavior did not affect our overall results, but improvements in the reduced gravity apparatus, such as devices that use air pressure to simulate reduced gravity (Whalen et al., 1994), could be useful for future research. Future research is also needed to explain why the individual estimates for weight support, propulsion and leg swing sum to ~125% of the actual net metabolic cost of running. Combining weight support, loading, aiding horizontal force and assisting leg swing might reveal the interactions of these effects. Previous studies of the metabolic cost of leg swing in running have shown varied results in different species (Marsh et al., 2004; Modica and Kram, 2005; Moed and Kram, 2005). Therefore, additional studies addressing the metabolic cost of leg swing are warranted. In the present study, we measured the metabolic cost of running only at 3 m s⁻¹ over level ground. Future studies should test the effect of speed and incline on the metabolic cost of running and the contributions of these factors. Finally, plans are currently

underway for humans to return to the moon. Therefore, studies of running with added mass (i.e. life support systems) in reduced lunar gravity using our techniques could be useful for calculating oxygen requirements.

Conclusions

We found that reducing body weight during running with the rolling trolley simulated reduced gravity method results in substantial but less than proportional decreases in metabolic cost. Therefore, contrary to some previous conclusions (Taylor et al., 1980; Kram and Taylor, 1990; Farley and McMahon, 1992), the metabolic cost of running is not entirely due to body weight support. Adding both mass and weight results in a slightly more than proportional increase in net metabolic cost. Finally, adding mass alone has little effect on the metabolic cost of running, but because horizontal impulses change little, adding mass alone is not an effective method for establishing the cost of braking/propelling body mass in running.

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