Obesity does not impair walking economy across a range of speeds and grades

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Browning RC, Reynolds MM, Board WJ, Walters KA, Reiser RF 2nd. Obesity does not impair walking economy across a range of speeds and grades. J Appl Physiol 114: 1125–1131, 2013. First published February 14, 2013; doi:10.1152/japplphysiol.00765.2012.—Despite the popularity of walking as a form of physical activity for obese individuals, relatively little is known about how obesity affects the metabolic rate, economy, and underlying mechanical energetics of walking across a range of speeds and grades. The purpose of this study was to quantify metabolic rate, stride kinematics, and external mechanical work during level and gradient walking in obese and nonobese adults. Thirty-two obese [18 women, mass = 102.1 (15.6) kg, BMI = 33.9 (3.6) kg/m²; mean (SD)] and 19 nonobese [10 women, mass = 64.4 (10.6) kg, BMI = 21.6 (2.0) kg/m²] volunteers participated in this study. We measured oxygen consumption, ground reaction forces, and lower extremity kinematics while subjects walked on a dual-belt force-measuring treadmill at 11 speeds/grades (0.50–1.75 m/s, −3° to +9°). We calculated metabolic rate, stride kinematics, and external work. Net metabolic rate (E_net/kg, W/kg) increased with speed or grade across all individuals. Surprisingly and in contrast with previous studies, E_net/kg was 0–6% less in obese compared with nonobese females during level and uphill (4%) walking at 1.0 m/s, but was greater in the obese women when walking at 1.3 m/s up a 4% incline. Collectively, these findings suggest that obesity-related differences in E_net/kg and economy are affected by walking speed and grade. If so, estimates of energy expenditure and aerobic demand using standard prediction equations may be inaccurate for these individuals, limiting our ability to develop comprehensive walking guidelines for weight management.

During walking, metabolic energy is required to perform work to lift and accelerate the center of mass [external work (W_ext)], support body weight, swing the limbs, and maintain balance. Thus differences in walking W_net/kg and economy due to obesity may be associated with these tasks. Although W_ext/kg (J/kg) is a primary determinant of level walking metabolic rate (9, 16), W_ext/kg during level walking is similar in obese compared with nonobese adults (7, 25, 33). No studies have quantified W_ext/kg in obese adults during uphill or downhill walking; thus we do not know whether obese individuals will alter their gait in a way that affects W_ext/kg and, consequently, E_net/kg. Given that obese individuals have reduced relative leg strength (23) and a greater proportion of the less efficient type IIb muscle fibers (38) compared with nonobese adults, the metabolic rate associated with supporting body weight and swinging the legs, particularly during uphill walking, may be greater in obese individuals (20). If so, body mass, body composition, and distribution of fat mass (e.g., ratio of trunk to leg fat mass) should be associated with an increase in E_net/kg and a decrease in walking economy across a range of speeds and grades. In addition, obese individuals walk with wider steps (5) and greater lateral leg swing circumduction compared with nonobese individuals (31), and these adaptations may also be associated with an increase in E_net/kg (33).

OBESITY PREVALENCE AND THE ASSOCIATED RISKS FOR CHRONIC DISEASE

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were not taking any medications known to alter metabolism, and body mass was stable (<2.5 kg change during the previous 3 mo). All nonobese subjects had a body mass index (BMI) <25 kg/m², while obese subjects had a BMI between 30 and 50 kg/m² (Table 1). Subjects gave written, informed consent that followed the guidelines of, and was approved by, the Colorado State University Human Research Institutional Review Board.

**Experimental protocol.** Each subject completed three experimental sessions. Details of these sessions have been described previously (11), but are outlined briefly here. The first visit included a physical examination, body composition analysis using dual-energy X-ray absorptiometry (Hologic Discovery, Bedford, MA) and a graded exercise test to determine maximal VO₂ (VO₂peak). We determined percent body fat and percent lean mass for the entire body and three regions of interest (thigh, shank, and foot) from the dual-energy X-ray absorptiometry image. To estimate the distribution of adipose tissue, we also calculated the ratio of trunk to leg fat mass for each individual. We used a modified Balke treadmill protocol to determine each subject’s VO₂peak. We determined VO₂ via open-circuit respirometry (Oxycon Mobile, Yorba Linda, CA), with expired gas data averaged every 30 s.

During the second and third sessions, we collected metabolic and biomechanics data as subjects stood and walked (with shoes) at 11 speed/grade combinations (5–6 sessions). Treadmill speeds ranged from 1.50 to 1.75 m/s in increments of 0.25 m/s (six total), and grades were 3°, 0, 3, 6, and 9° (Table 2). Treadmill speed/grade combinations were selected to elicit moderate-vigorous intensities (18). Trials were 6 min in duration, and subjects were allowed 5 min of rest between trials. Subjects were also given an acclimatization period before data collection by walking at a comfortable pace on the level treadmill for up to 10 min.

**Energetic measurements.** To determine metabolic rate during standing and walking, we measured the rates of VO₂ and carbon dioxide production (VCO₂) using the same metabolic system described above. We calibrated the system and measured standing metabolic rate for 6 min before collecting the walking data. Subjects were allowed 4 min to reach steady state (no significant increase in VO₂ during the final 2 min and a respiratory exchange ratio <1.0), and we calculated the average VO₂ and VCO₂ (l/min) for the final 2 min of each trial. Relative aerobic intensity was determined by dividing the measured VO₂ by the VO₂peak of each individual. We then calculated E gross (W) and mass-specific gross metabolic rate (E gross/kg, W/kg) from VO₂ and VCO₂ using a standard equation (3) and subtracted standing metabolic rate from the walking values to derive mass-specific Emet/kg (W/kg). We also calculated mass-specific VO₂peak/kg (W/kg) from measured VO₂ using a conversion of 20.1 J/L O₂.

**Biomechanics measurements.** To quantify stride kinematics, step width, lateral leg swing, and Wext/kg, we used a dual-belt, inclinable, force-measuring treadmill (Fully Instrumented Treadmill, Bertec, Columbus, OH). Ground reaction forces (GRF) and moments were not taken into account.

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**Table 1. Physical characteristics of participants**

<table>
<thead>
<tr>
<th>Subject Characteristics</th>
<th>Obese</th>
<th>Nonobese</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>32</td>
<td>19</td>
</tr>
<tr>
<td>Age, yr</td>
<td>28.9 (7.6)</td>
<td>22.8 (3.6)</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.73 (0.09)</td>
<td>1.72 (0.09)</td>
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<tr>
<td>Body mass, kg</td>
<td>102.1 (15.6)</td>
<td>64.4 (10.6)</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>33.9 (3.6)</td>
<td>21.6 (2.0)</td>
</tr>
<tr>
<td>Body fat, %</td>
<td>39.7 (6.8)</td>
<td>24.7 (7.5)</td>
</tr>
<tr>
<td>Lean body mass, kg</td>
<td>59.4 (12.9)</td>
<td>45.5 (10.1)</td>
</tr>
<tr>
<td>Trunk-to-leg fat mass ratio</td>
<td>1.61 (0.46)</td>
<td>1.13 (0.29)</td>
</tr>
</tbody>
</table>

**Values are means (SD); n, no. of subjects. BMI, body mass index; VO₂peak, maximal oxygen uptake.**

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**Table 2. Oxygen consumption and metabolic rate for each speed/grade combination**

<table>
<thead>
<tr>
<th>Speed, m/s, Grade, °</th>
<th>VO₂, l/min</th>
<th>E gross, W</th>
<th>E gross/kg, W/kg</th>
<th>Emet/kg, W/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obese</td>
<td>Nonobese</td>
<td>Obese</td>
<td>Nonobese</td>
</tr>
<tr>
<td>0.50, 9</td>
<td>1.42 ± 0.04</td>
<td>1.04 ± 0.05</td>
<td>482.3 ± 12.7</td>
<td>350.5 ± 16.9</td>
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<tr>
<td>0.75, 6</td>
<td>1.51 ± 0.04</td>
<td>1.08 ± 0.04</td>
<td>513.5 ± 14.8</td>
<td>363.2 ± 14.8</td>
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<tr>
<td>0.75, 9</td>
<td>1.91 ± 0.05</td>
<td>1.34 ± 0.05</td>
<td>658.0 ± 18.5</td>
<td>455.4 ± 17.8</td>
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<tr>
<td>1.00, 3</td>
<td>1.37 ± 0.04</td>
<td>1.02 ± 0.04</td>
<td>466.0 ± 13.3</td>
<td>343.2 ± 14.8</td>
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<td>1.00, 6</td>
<td>1.83 ± 0.04</td>
<td>1.34 ± 0.05</td>
<td>630.0 ± 15.1</td>
<td>454.7 ± 16.9</td>
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<tr>
<td>1.25, -3</td>
<td>1.10 ± 0.05</td>
<td>0.70 ± 0.03</td>
<td>310.2 ± 9.2</td>
<td>235.8 ± 11.2</td>
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<td>1.25, 0</td>
<td>1.18 ± 0.04</td>
<td>0.85 ± 0.04</td>
<td>398.5 ± 13.3</td>
<td>287.1 ± 13.9</td>
</tr>
<tr>
<td>1.25, 3</td>
<td>1.64 ± 0.04</td>
<td>1.18 ± 0.05</td>
<td>559.7 ± 14.7</td>
<td>399.1 ± 16.7</td>
</tr>
<tr>
<td>1.50, 0</td>
<td>1.45 ± 0.04</td>
<td>1.01 ± 0.05</td>
<td>493.3 ± 14.4</td>
<td>341.9 ± 15.3</td>
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<tr>
<td>1.50, 3</td>
<td>1.98 ± 0.06</td>
<td>1.40 ± 0.05</td>
<td>684.9 ± 18.8</td>
<td>476.9 ± 18.7</td>
</tr>
<tr>
<td>1.75, 0</td>
<td>1.87 ± 0.06</td>
<td>1.26 ± 0.05</td>
<td>643.9 ± 21.6</td>
<td>428.4 ± 18.1</td>
</tr>
</tbody>
</table>

**Values are means ± SE. VO₂ gross oxygen consumption; E gross, gross metabolic rate; E gross/kg, mass-specific gross metabolic rate; Emet/kg, mass-specific net metabolic rate. Bold indicates that obese value is significantly different than nonobese for that speed/grade combination.**
recorded at 1,000 Hz by force platforms embedded under each treadmill belt. We also recorded lower extremity kinematics via a seven-camera motion capture system operating at 100 Hz (Nexus, Vicon, Centennial, CO). Passive reflective markers were placed on each subject according to a modified Helen Hayes marker set (21). Data were collected for 30 s during the final minute of each trial. Raw kinetic and kinematic data were smoothed using a fourth-order, zero-lag, digital Butterworth filter with a cutoff frequency of 12 and 5 Hz, respectively. We used the vertical GRF and a 15-N threshold to determine heel-strike and toe-off and then determined stride kinematics [stride length, stride frequency, double support, and duty factor (percentage of stride spent in stance)] for each trial. Step width was calculated as the distance between the midstance center of pressure of the right and left leg during consecutive steps of each trial. We defined lateral leg swing as the mediolateral distance between the lateral knee marker at toe-off and midswing. We quantified individual limb $W_{\text{ext/kg}}$, as described in detail by Donelan et al. (10). Briefly, we calculated center-of-mass velocities from the GRF data and computed mechanical power as the dot product of the individual limb GRF and center-of-mass velocities. We then calculated $W_{\text{ext/kg}}$ by integrating the mechanical power for each step. We report total positive ($W_{\text{ext/kg}}$) and negative $W_{\text{ext/kg}}$ per step ($W_{\text{neg/kg}}$), which is the sum of the $W_{\text{ext/kg}}$ performed by leading and trailing limb during double support and the $W_{\text{ext/kg}}$ performed by the stance limb during single support. Finally, we calculated the normalized rate of total positive external work ($P_{\text{ext/kg}} / W_{\text{kg}}$), by dividing $W_{\text{ext/kg}}$ by step period.

**Statistical analysis.** Statistical analysis was performed with SAS version 9.2 (SAS Institute, Cary, NC). A separate repeated-measures ANOVA was fit for each energetic and biomechanical response variable (e.g., $V\dot{O}_2$, $E_{\text{gross/kg}}$, $W_{\text{ext/kg}}$) using the SAS mixed procedure. The models included fixed effects corresponding to obesity status, sex, speed/grade, and all interactions of these terms. The model also included a random subject effect to account for repeated measures for each subject. Linear contrasts were used to test for differences in means of obese vs. nonobese participants at each speed and grade. The $P$ values corresponding to these contrasts were adjusted using Bonferroni multiple testing adjustment to account for the 11 speed/grade combinations. Residual diagnostics plots were examined. Some of the variables showed evidence that assumptions of equality of variance and normality may not be met. However, the departures were not severe. We considered using a log (natural log) transformation, which did help satisfy assumptions, but did not change the main conclusions. Hence, for simplicity, we present the results of the analysis on the original scale.

To develop equations to estimate mass-specific $V\dot{O}_2$, and $E_{\text{gross/kg}}$, we computed hierarchical linear regression of treadmill, anthropometric, and biomechanical variables onto $V\dot{O}_2$, and $E_{\text{gross/kg}}$. For estimating $V\dot{O}_2$, we entered treadmill speed and grade into the first block, body mass into the second block, and age into the third block. For estimating $E_{\text{gross/kg}}$, the first two blocks were the same as for $V\dot{O}_2$, and then we entered %body fat, trunk-to-leg fat mass ratio, step width, lateral leg swing, double support, and age into the third block. The $E_{\text{net/kg}}$ prediction errors for $V\dot{O}_2$, and $E_{\text{gross/kg}}$ were less than 10%. For estimating $E_{\text{net/kg}}$, the first block was BMI, second block was $V\dot{O}_2$, and then the %body fat, trunk-to-leg fat mass ratio, step width, lateral leg swing, double support, and age were entered into the third block. The $E_{\text{net/kg}}$ prediction errors for $V\dot{O}_2$, and $E_{\text{gross/kg}}$ were less than 10%. For estimating $E_{\text{net/kg}}$, the first block was BMI, second block was $V\dot{O}_2$, and then the %body fat, trunk-to-leg fat mass ratio, step width, lateral leg swing, double support, and age were entered into the third block. The $E_{\text{net/kg}}$ prediction errors for $V\dot{O}_2$, and $E_{\text{gross/kg}}$ were less than 10%.

**RESULTS**

Energetics. Most trials required a moderate relative aerobic intensity of between 40 and 60% of subjects’ $V\dot{O}_2$ peak (Fig. 1). However, when the obese individuals walked at the fastest speeds at each grade, their relative aerobic intensity exceeded the moderate threshold. Relative aerobic intensities were $\sim 8–15\%$ greater across all speeds/grades ($P < 0.001$) for obese compared with nonobese individuals, due primarily to the lesser $V\dot{O}_2$ peak of the obese participants.

All metabolic variables ($V\dot{O}_2$, $E_{\text{gross}}$, $E_{\text{gross/kg}}$, and $E_{\text{net/kg}}$) significantly increased with walking speed and/or grade ($P < 0.001$, Table 2). Obese individuals walked with significantly greater $V\dot{O}_2$ and $E_{\text{gross}}$ compared with nonobese individuals across all speeds and grades ($P < 0.001$, Table 2, Fig. 2A). However, $E_{\text{gross/kg}}$ was significantly less in obese vs. nonobese individuals across all speeds and grades ($P < 0.001$), and $E_{\text{net/kg}}$ was significantly less in obese vs. nonobese individuals at 5 of the 11 speed/grade combinations ($P = 0.014$ for main effect of obesity, Table 2, Fig. 2B). Men had significantly greater $V\dot{O}_2$ and $E_{\text{gross}}$ compared with women across all speeds and grades ($P = 0.002$ for both), but this was due to their greater body mass, as there was no significant effect of sex on $E_{\text{gross/kg}}$ and $E_{\text{net/kg}}$ ($P = 0.869$ and $P = 0.377$, respectively). In addition, there were no significant interactions between the fixed effects (sex, obesity, and speed/grade) and $E_{\text{gross/kg}}$ and $E_{\text{net/kg}}$. $E_{\text{gross/kg}}$ was $\sim 7\%$ greater in nonobese individuals compared with obese individuals during level walking at 1.50 m/s and $\sim 20\%$ greater when walking at 1.25 m/s, $–3\%$. Differences in $E_{\text{net/kg}}$ between obese and nonobese individuals were not significant during level walking (1.25, 1.50, and 1.75 m/s) and uphill walking at the slowest speeds (0.50 and 0.75 m/s), but values were $\sim 4–12\%$ less in obese compared with nonobese individuals during the gradient walking trials at the faster speeds (1.00, 1.25, and 1.50 m/s).

Biomechanics. Temporal-spatial kinematics were affected by speed/grade and, in some cases, obesity. As walking speed decreased, stride length and stride frequency decreased, while double support time and duty factor increased (main effect of speed/grade for all variables, $P < 0.001$). Compared with nonobese individuals, obese individuals walked across all speed/grade combinations with similar stride length/frequency ($P = 0.66$ and 0.99,
resulted in the following equations to estimate \( \dot{V}O_2/kg \) and obesity (Fig. 3). Wstep/kg

Duty factor, %stance 65.8
Stride frequency, Hz 0.85

Greater in obese at intermediate speeds/grades (Fig. 3).

Stride length, m 1.31

Table 3. Temporal stride kinematics

<table>
<thead>
<tr>
<th>Kinematics Variable</th>
<th>Obese</th>
<th>Nonobese</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stride length, m</td>
<td>1.31 ± 0.02</td>
<td>1.31 ± 0.02</td>
</tr>
<tr>
<td>Stride frequency, Hz</td>
<td>0.85 ± 0.01</td>
<td>0.85 ± 0.01</td>
</tr>
<tr>
<td>Duty factor, %stance</td>
<td>65.8 ± 0.2</td>
<td>63.4 ± 0.2</td>
</tr>
<tr>
<td>Double support, %stride</td>
<td>31.0 ± 0.4</td>
<td>26.6 ± 0.4</td>
</tr>
<tr>
<td>Step width, m</td>
<td>0.207 ± 0.002</td>
<td>0.167 ± 0.002</td>
</tr>
<tr>
<td>Lateral leg swing, m</td>
<td>0.040 ± 0.001</td>
<td>0.035 ± 0.001</td>
</tr>
</tbody>
</table>

Values are means ± SE for all speeds/grades. Bold indicates that obese value is significantly different than nonobese (all \( P < 0.001 \)).
tially accept our hypothesis that several anthropometric and biomechanical variables would be related to $E_{\text{net/kg}}$. According to the equation developed to estimate $E_{\text{net/kg}}$, step width was positively related to $E_{\text{net/kg}}$, while trunk-to-leg fat mass ratio, double support duration, and age were negatively related to $E_{\text{net/kg}}$.

As expected, metabolic rate was influenced by walking speed and grade. Obese individuals had a much greater gross $V_{\text{O2}}$ and metabolic rate compared with their nonobese counterparts, a finding supported by other studies (4, 22, 33). We found that $V_{\text{O2}}$ (l/min) and $E_{\text{gross}}$ (W) were 35–50% greater in obese vs. nonobese participants. These results support our recent finding that obese individuals can achieve recommended exercise intensities while walking slowly up a moderate incline (11). For example, walking at 0.75 m/s up a 6° incline required ~52% $V_{\text{O2\,peak}}$ in our obese participants, whereas level walking at 1.50 m/s required ~50% $V_{\text{O2\,peak}}$. These results also highlight the difficulty obese individuals may have if attempting to walk up moderately steep grades at faster speeds (>1.25 m/s), as the relative aerobic intensity could easily exceed a sustainable intensity. Somewhat surprisingly, when obese individuals walked down a 3° grade at 1.25 m/s, they still required nearly 40% $V_{\text{O2\,peak}}$, suggesting that moderate downhill grades may also offer an alternative form of moderate-intensity PA, although the risks of musculoskeletal injury may increase due to the large eccentric muscle forces required to maintain a steady walking speed.

Our data set allowed the development of an equation to estimate $V_{\text{O2/kg}}$ across a range of body size/composition, walking speeds, and positive and negative grades. This equation may be useful to estimate both relative aerobic effort, as well as associated energy expenditure during treadmill walking, particularly because it includes easily determined variables. We found that treadmill speed and grade were the primary contributors to the prediction model ($R^2 = 0.69$), but that body mass and age were also significant predictors of $V_{\text{O2/kg}}$ (change ($\Delta$) in $R^2$ of 0.06 and 0.02, respectively). The finding that body mass and age were negatively associated with $V_{\text{O2/kg}}$ was unexpected, and it is possible that heavier and/or older (e.g., middle aged) individuals may become adapted to walking with the added mass, presumably because they have had more time to do so. However, our data did not include individuals older than 50 yr. Therefore, our prediction equation may not estimate $V_{\text{O2/kg}}$ accurately for older individuals (>50 yr), particularly given that older individuals have a greater walking metabolic rate than younger individuals (24). We used the PRESS method to cross-validate our prediction equation, and, while the results suggest that the equation has good validity, the PRESS method does not guard against a Type II error or assign causation. Future studies are needed to validate this new equation using an independent sample. We also used the American College of Sports Medicine prediction equation [see Table 4 (14)] to estimate $V_{\text{O2/kg}}$ for our data, but we found that this equation only explained 50% of the variance in $V_{\text{O2/kg}}$ (compared with 77% in the new equation). This suggests that the new prediction equation may offer a more accurate estimate of $V_{\text{O2}}$ during gradient and level treadmill walking than the commonly used in the American College of Sports Medicine prediction equation.

We did not expect to find that $E_{\text{net/kg}}$ of obese individuals would be less than or equal to $E_{\text{net/kg}}$ of nonobese individuals. Although the significant differences in $E_{\text{net/kg}}$ between groups were typically small (~5%), our results suggest that obese adults walk with similar or slightly better economy compared with nonobese adults. Our results are not in agreement with the few studies that have reported or suggested that walking $E_{\text{net/kg}}$ is ~10% greater in obese vs. nonobese adults (4, 22, 29) at typical or fast level walking speeds (1.25–1.75 m/s). The $E_{\text{net/kg}}$ reported here for moderately obese individuals are similar to those reported by other studies, including our own (4, 6, 22). As a result, we are confident that our metabolic data for obese individuals are representative. Our nonobese $E_{\text{net/kg}}$ values are also within the range of values reported in the walking energetics literature (8, 34, 35), but are greater than those reported in the studies that have directly compared obese and nonobese adults (4, 6, 22). A potential explanation for the greater $E_{\text{net/kg}}$ of nonobese adults in our study compared with other studies is the inherent variability in metabolic measures (both standing and walking). Notably, Rubenson et al. (35) recently reported that there is considerable variability in walking metabolic rates of nonobese adults, with minimum net metabolic costs ranging from 1.71 to 2.59 J·kg$^{-1}$·m$^{-1}$ (42% of mean value of 2.06 J·kg$^{-1}$·m$^{-1}$). This variability is likely due, in part, to methodological differences between studies, including population (e.g., sex, sedentary), methods of indirect calorimetry, measurement of standing metabolic rate, and acclimation to the protocol/equipment (if walking on a treadmill). Clearly, future studies that use large sample sizes, a control group, and standardized standing and walking protocol are needed to confirm our results.

Studies that have quantified the energetics of load-carrying during incline walking provide additional support for relatively good uphill walking economy in obese adults. Load-carrying studies have reported that $V_{\text{O2/kg}}$ and $E_{\text{net/kg}}$, when normalized by total mass (body mass plus load), are similar or smaller compared with unloaded walking (17, 36). Thus, if obesity is considered analogous to walking with added mass, one would expect that obese adults may be as or more economical than.

<table>
<thead>
<tr>
<th>Prediction Equation</th>
<th>Variable Coefficients</th>
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<tbody>
<tr>
<td>$V_{O2/kg}$, W/kg</td>
<td>Constant</td>
</tr>
<tr>
<td>$E_{\text{net/kg}}$, W/kg</td>
<td></td>
</tr>
<tr>
<td>$V_{O2/kg}$, ml·kg$^{-1}$·min$^{-1}$</td>
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<tr>
<td>ACSM $V_{O2/kg}$, ml·kg$^{-1}$·min$^{-1}$</td>
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</tbody>
</table>

$V_{O2/kg}$, mass-specific $V_{O2}$; ACSM, American College of Sports Medicine. The ACSM prediction equation is: $V_{O2/kg} = 0.1$ (speed) + 1.8 (speed) × (fractional grade) + 3.5, where speed has units of m/min.
their nonobese counterparts. Further support for the finding that obese adults may have relatively good walking economy can be found in studies that have investigated habitual load carriers (e.g., porters). Two studies have reported that Himalayan porters walked with much better economy compared with their European mountaineering counterparts (nonhabituated) when carrying substantial loads (1, 30). Collectively, our results and these studies suggest that perhaps we should expect obese adults to have similar or smaller mass-specific walking metabolic rates and better economy compared with nonobese adults, particularly when walking uphill.

By simultaneously quantifying metabolic and biomechanical characteristics of walking, we gained insights into how obesity affects the energetics and economy of walking. We found a strong correlation between P\textsuperscript{+}\textsubscript{step/kg} and E\textsubscript{net/kg}, demonstrating that work done to lift and accelerate the center of mass is an important determinant of E\textsubscript{net/kg}. However, the similarity in W\textsubscript{ext/kg} in obese and nonobese individuals suggests that this work is not affected by obesity, as has been reported in other studies (7, 25, 33). Although W\textsubscript{step/kg} was not different between the groups, W\textsubscript{step/kg} was slightly, but significantly, greater in the obese individuals at some same speed/grades (e.g., 3° trials). However, the net W\textsubscript{ext/kg} was similar in both groups at these speed/grades. While our results suggest that obesity does not elicit changes in walking mechanics that reduce the W\textsubscript{ext/kg}, not all W\textsubscript{ext/kg} is performed by muscles. W\textsubscript{ext/kg} may also be performed by soft tissues that rebound after the leading limb’s collision with the ground and perform positive work (40). This soft tissue positive work may reduce E\textsubscript{net/kg} through a reduction in muscle work and may be one explanation for the relatively good walking economy of obese individuals. Future studies that quantify both center of mass and joint work will illuminate how work done by soft tissue affects the economy of walking in obese individuals.

We included several anthropometric and biomechanical variables thought to be associated with body weight support, leg swing, and balance in a linear regression analysis to determine how obesity affected the metabolic rate and walking economy associated with these tasks. We found, as has been reported previously, that obese adults spent more time in stance and double support (relative to stride time), walked with wider steps, and had a greater lateral leg swing compared with their nonobese peers (5, 33, 37). Neither body mass nor composition were found to significantly improve the ability to predict E\textsubscript{net/kg}, which we interpret to mean that the metabolic rate associated with body weight support is not affected by obesity. The inclusion of trunk-to-leg fat mass ratio (ΔR\textsuperscript{2} = 0.01) and step width (ΔR\textsuperscript{2} = 0.01) in our prediction equation suggests that swinging/lifting heavier legs and walking with wider steps is associated with a slightly greater metabolic rate, but lateral leg swing is not. In addition, double support duration was negatively associated with metabolic rate (ΔR\textsuperscript{2} = 0.02), and we hypothesize that obese individuals may increase double support time to maintain balance/stability, which may, in turn, act to reduce E\textsubscript{net/kg} (32). We did not expect age to be a significant predictor of E\textsubscript{net/kg} and in fact its contribution to the ability to estimate E\textsubscript{net/kg} is small (ΔR\textsuperscript{2} = 0.002). While our findings may seem at odds with studies that report older adults (>60 yr old) have a greater E\textsubscript{net/kg} than younger adults (28), we did not include older individuals in this study. Therefore, the resulting prediction equation is not likely to be applicable to an older population. The inclusion of age as a predictor of E\textsubscript{net/kg} suggests that, as individuals age, they are able to adapt to changes in body mass. Collectively, these results indicate that obese individuals’ heavier legs and wider steps are associated with reduced walking economy, but this is offset by an increased double support time, which is associated with improved walking economy. However, our results indicate that each of these variables makes a relatively minor contribution to predicting metabolic rate and is a potential, but not proven, determinant of metabolic rate. Future studies that provide body weight and/or leg swing support and stability and quantify obesity onset are needed to confirm the roles that these variables play in walking metabolic rate and economy.

Conclusions. Our results suggest that, while obese adults require a greater amount of metabolic energy to walk, they can easily achieve recommended exercise intensities walking uphill slowly. We have developed new prediction equations that can be used to estimate V\textsubscript{O2} and metabolic rate across a range of walking speeds/grades and levels of adiposity. We found that obese adults walk with a similar or smaller mass-specific E\textsubscript{net/kg}, suggesting these individuals have equivalent or better walking economy compared with their nonobese counterparts. The external work required to lift and accelerate the body, although a primary determinant of E\textsubscript{net/kg}, was not affected by obesity across the range of speeds/grades used in this study. E\textsubscript{net/kg} was positively related to relative leg mass and step width and negatively related to double support duration. These results suggest that obesity does not impair walking economy across a range of walking speeds and grades.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS


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