Do mechanical gait parameters explain the higher metabolic cost of walking in obese adolescents?

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Net metabolic cost of walking normalized by body mass (C_W-BM; in J·kg⁻¹m⁻¹) is greater in obese than in normal-weight individuals, and biomechanical differences could be responsible for this greater net metabolic cost. We hypothesized that, in obese individuals, greater mediolateral body center of mass (COM) displacement and lower recovery of mechanical energy could induce an increase in the external mechanical work required to lift and accelerate the COM and thus in net C_W-BM. Body composition and standing metabolic rate were measured in 23 obese and 10 normal-weight adolescents. Metabolic and mechanical energy costs were assessed while walking along an outdoor track at four speeds (0.75–1.50 m/s). Three-dimensional COM accelerations were measured by means of a tri-axial accelerometer and gyroscope and speeds (0.75–1.50 m/s). Three-dimensional COM accelerations were measured by means of a tri-axial accelerometer and gyroscope and integrated twice to obtain COM velocities, displacements, and fluctuations in potential and kinetic energies. Last, external mechanical work (J·kg⁻¹m⁻¹), mediolateral COM displacement, and the mechanical energy recovery of the inverted pendulum were calculated. Net C_W-BM was 25% higher in obese than in normal-weight subjects on average across speeds, and net C_W-BM₁ (J·kg⁻⁰·⁶⁷m⁻¹) was significantly related to percent body fat (r² = 0.46). However, recovery of mechanical energy and the external work performed (J·kg⁻¹m⁻¹) were similar in the two groups. The mediolateral displacement was greater in obese subjects and significantly related to percent body fat (r² = 0.64). The mediolateral COM displacement, likely due to greater step width, was significantly related to net C_W-BM (r² = 0.49). In conclusion, we speculate that the greater net C_W-BM₁ in obese subjects may be partially explained by the greater step-to-step transition costs associated with wide gait during walking. 

Obesity; mediolateral displacement; mechanical work; energy cost

The most important factor responsible for excessive gain in body fat mass in children is the long-term imbalance between energy intake and energy expenditure (e.g., Ref. 30). The amount of energy expended during physical activity plays an important role in the prevention of overweight and obesity and in the weight-loss process. However, obese children and adolescents spend less time than their normal-weight peers on moderate physical activities such as walking and more time on sedentary activities (21, 23). This could be partly due to the difficulty of performing activities in which obese persons move or raise their larger body mass (BM) against gravity (39). Walking is a convenient form of daily physical activity that is recommended for obese individuals (2), despite the fact that, at a given walking speed, a higher percentage of maximal oxygen uptake and a higher metabolic energy expenditure have been reported in this population (21, 28). Consequently, physical inactivity in obese adolescents (often linked to a positive energy balance) may be partly due to the difficulty to perform daily activities such as walking (20, 34), making it relevant to fully understand the origin(s) of the high cost of walking (39).

Obese children and adolescents, as defined by a body mass index (BMI; in kg/m²) above the cutoff values reported by Cole et al. (10), and class II obese adults [BMI of 30–40 kg/m² (41)] have been shown to expend much more metabolic energy than normal-weight subjects at a given walking speed, especially at high speeds (4, 6, 21, 22, 38). In obese adolescents, a 71–84% greater gross metabolic rate (W) has been reported for walking speeds ranging from 1.1 to 1.7 m/s (21). Even when normalizing by both walking speed (m/s) and BM, gross metabolic cost of walking (gross C_W-BM; in J·kg⁻¹m⁻¹) is still 25% higher in obese adolescents (21), and net (ground-stationing) C_W-BM₁ is 10% higher in obese adults (4, 6) compared with their age-matched counterparts. These results suggest that BMI is not the only determinant of C_W-BM₁. However, other studies reported similar values of net and gross metabolic rate for both obese and normal-weight children after normalizing to BM or to fat-free mass (FFM; in kg) (22, 38), perhaps due to the low degree of subjects’ obesity (BMI of 24.6–28.4 kg/m², which is close to the cutoff values for obesity relative to chronological age). In obese adults, Browning et al. (4) reported that net metabolic rate (W/kg) was positively related to percent body fat, partly due to association of a lower standing metabolic rate per kilogram of BM with greater total body fat mass.

In obese individuals, many studies have suggested but never shown that, in addition to an extra load, biomechanical changes in walking pattern could be responsible for a greater net C_W-BM₁ (4, 6, 24, 25, 39) rather than a decrease in muscular efficiency or cardiorespiratory deconditioning (28). For instance, greater step width has been reported in obese individuals due to an excessive amount of adipose tissue in the lower limbs, hence a larger thigh circumference (5, 37). Greater step width is associated with other differences in walking kinematics, such as greater leg swing circumduction, and has been shown to increase net C_W-BM₁ (12, 35). Moreover, the greater step width and mediolateral (M-L) ground reaction forces (GRF) (5) could be responsible for the greater M-L displacement of the center of mass (COM) observed in obese adults (24). It has also been shown that obese children are mechanically less efficient at transferring energy across the hip (27) and that obese adults walk with lower recovery of mechanical energy at preferred walking speed (24). Indeed, walking is characterized by an inverted pendulum mechanism of energy interchange (9). During the transition from one inverted pendulum arc to the next, some energy is lost in redirecting the

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COM velocity, which requires an external mechanical work (\(W_{\text{ext}}\)) to lift and accelerate the COM in the three planes of movement (vertical, anteroposterior, and mediolateral) (8). Therefore, a concomitant increase in the fluctuation of M-L kinetic energy (24) with a decrease in recovery of mechanical energy (due to an impaired inverted pendulum mechanism) could increase \(W_{\text{ext}}\). Consequently, in obese adolescents, quantifying M-L COM displacement, the integrity of the inverted pendulum mechanism of energy interchange and \(W_{\text{ext}}\) at several walking speeds seems necessary to fully understand their walking pattern, especially because \(W_{\text{ext}}\) accounts for about one-half of the net \(C_{W-BM}^{-1}\) in adults (17).

Moreover, net and gross \(C_{W}\) are commonly normalized by BM, without taking account of the nonproportionality between the two factors, which yields a variable still dependent on BM. An appropriate normalization of \(C_{W}\) is therefore necessary to understand the contributions of other factors, and a scaling exponent of 0.67–0.75 for the normalization of \(C_{W}\) by BM has been shown to be suitable for human walking (7, 19, 32, 40, 42). In adolescents, \(C_{W}\) normalized by BM raised to the 0.67 power \((C_{W-BM}^{-1}\)) in J·kg\(^{-0.67}\)·m\(^{-1}\) provides a more appropriate method of comparison than with the standard normalization by BM (42).

The primary purpose of this study was to compare net \(C_{W-BM}^{-1}\), mechanical parameters of the walking gait (recovery of mechanical energy, M-L COM displacement, and \(W_{\text{ext}}\)), and mechanical efficiency between obese and normal-weight adolescents at several walking speeds. The secondary purpose was to determine the effects of percent body fat on mechanical parameters and net \(C_{W-BM}^{-1}\), and the effects of changes in mechanical parameters on net \(C_{W-BM}^{-1}\).

We hypothesized that, in obese individuals, both greater mediolateral COM displacement and lower recovery of mechanical energy led to an increase in \(W_{\text{ext}}\), and thereby in net \(C_{W-BM}^{-1}\). To the best of our knowledge, no study has investigated both metabolic and biomechanical measures to determine whether changes in mechanical gait pattern in obese adolescents are related to the greater net \(C_{W-BM}^{-1}\).

**Glossary**

| 3-D | Three dimensional |
| BM | Body mass |
| BMI | Body mass index |
| COM | Center of mass of the body |
| \(C_{W}\) | Metabolic cost of walking (J/m) |
| \(C_{W-BM}^{-0.67}\) | Metabolic cost of walking normalized by \(BM^{0.67}\) (J·kg\(^{-0.67}\)·m\(^{-1}\)) |
| \(C_{W-BM}^{-1}\) | Metabolic cost of walking normalized by \(BM^{1}\) (J·kg\(^{-1}\)·m\(^{-1}\)) |
| \(E_{k}\) | Total kinetic mechanical energy of the center of mass of the body |
| \(E_{p}\) | Gravitational potential energy of the center of mass of the body |
| \(E_{\text{tot}}\) | Total mechanical energy of the center of mass of the body |
| FFM | Fat-free mass |
| \(g\) | Gravitational acceleration |
| GRF | Ground reaction forces |
| \(h\) | Vertical change in position of the center of mass of the body |
| \(m\) | Mass |
| M-L | Mediolateral |
| SD | Standard deviation |
| \(V\) | Velocity of the center of mass of the body |
| \(V_{\text{CO}_2}\) | Rate of carbon dioxide production |
| \(V_{\text{O}_2}\) | Rate of oxygen consumption |
| \(W_{\text{ext}}\) | External mechanical work performed to lift and accelerate the center of mass of the body |
| \(W_{\text{int}}\) | Internal work |
| \(W_{\text{int,dc}}\) | Internal work done by one leg against the other during double contact |
| \(W_{k}\) | Work done to accelerate the center of mass of the body |
| \(W_{p}\) | Gravitational potential energy changes of the center of mass of the body |

**MATERIALS AND METHODS**

**Participants**

The present study included 33 adolescents: 23 obese (10 boys) and 10 normal-weight (10 boys) subjects with no orthopedic or neurological disorders and not receiving any medication that could interfere with their walking pattern or influence their energetic metabolism. Obese subjects were slightly older than normal-weight subjects, but it has been shown that age does not influence the measured parameters after the age of 10 yr (33). The physical characteristics of both groups of subjects are presented in Table 1.

Subjects were categorized into normal-weight and obese according to their BMI, using the cutoff points for age and gender defined by Cole et al. (10). Obese and normal-weight subjects followed similar experimental protocols. Obese subjects underwent this protocol on day 1 or 2 of the obesity-management program they had been recruited for (i.e., 5 days/wk in a specialized institution for obesity management and weekend at home).

For each adolescent and his/her parents, the study was explained in detail, and written consent was obtained before the beginning of the study. This study was approved by the regional ethics committee and was performed in accordance with the declaration of Helsinki II.

**Experimental Procedures**

All subjects walked along a nearly circular track 25 m in length and 3 m in width. The slope of the track was tested every 1 m and ranged from −0.5 to +0.5%. The walking speed was controlled by means of markers set out every 5 m along the track, and the subjects were instructed to walk past the markers at a pace imposed by a metronome tone. An experimenter walked alongside each subject to help him/her match the required speed.

**Table 1. Characteristics of the subjects**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Obese Subjects((n = 23))</th>
<th>Normal-Weight Subjects((n = 10))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>14.4±1.5†</td>
<td>11.8±0.9</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>93.9±26.7†</td>
<td>41.8±8.0</td>
</tr>
<tr>
<td>Height, cm</td>
<td>163.1±11.0*</td>
<td>154.2±8.6</td>
</tr>
<tr>
<td>BMI, kg/m(^2)</td>
<td>34.8±7.1†</td>
<td>17.4±1.7</td>
</tr>
<tr>
<td>Percent body fat, %</td>
<td>42.2±6.5†</td>
<td>22.4±6.3</td>
</tr>
<tr>
<td>FFM, kg</td>
<td>53.6±13.4†</td>
<td>32.1±4.3</td>
</tr>
<tr>
<td>Standing metabolic rate, W</td>
<td>119.4±24.0†</td>
<td>91.9±27.4</td>
</tr>
<tr>
<td>Normalized standing metabolic rate, W/kg</td>
<td>1.33±0.30†</td>
<td>2.23±0.66</td>
</tr>
</tbody>
</table>

Values are means ± SD. BMI, body mass index; FFM, fat-free mass. Significant differences between obese and normal-weight subjects: *\(P < 0.05\);
†\(P < 0.01\).
For each subject, the standing rate of oxygen consumption (\(V_O^2\)) was first measured over 10 min. Then, they performed four 4-min tests at different walking speeds (0.75, 1, 1.25, and 1.5 m/s) in a randomized order, separated by 5 min of rest. Mechanical and metabolic parameters of walking were measured with two portable devices carried around the chest by the subjects.

**Measurements and Data Analysis**

**Anthropometry and body composition.** For a better precision in obese subjects, fat-free mass (FFM; the total mass of lean tissue), and body fat mass were measured by dual-energy X-ray absorptiometry (DEXA, QDR 4005, Hologic, Bedford, MA) (16). Percent body fat was calculated by dividing body fat mass by BM.

For the normal-weight subjects, skinfold thickness values were measured to the nearest millimeter in triplicate by the same experimenter at the biceps, triceps, subscapular, and suprailiac points on the right side of the body using a Harpenden skinfolds caliper (British Indicators, West Sussex, UK). At each point, the mean value for the three skinfold thicknesses was calculated. Slaughter’s equations (36) were used to calculate the estimated percent body fat. BM was measured with subjects standing without shoes and in similar light clothing on a portable digital scale (Seca model 873 Omega), and recorded to the nearest 0.1 kg. Body fat mass was obtained by multiplying percent body fat by BM, and FFM was calculated by subtracting body fat mass from BM. For all subjects, stature was measured to the nearest 0.5 cm using a standardized wall-mounted height board, and BMI was calculated as BM divided by height squared.

**Metabolic parameters.** The rates of \(V_O^2\) (in ml/min) and carbon dioxide production (\(V_C^2\); in ml/min) were measured using a breath-by-breath portable gas analyzer (K4b2, COSMED) that weighed <1 kg and recorded, and the data were stored over the entire session for each subject. The K4b2 unit, previously validated by Duffield et al. (15), was calibrated with standard gases before each session. Average \(V_O^2\) and \(V_C^2\) were calculated over 30 s taken during the last minute of each trial where \(V_O^2\) and \(V_C^2\) were stable within ±10%. Gross metabolic rate (W) for each 4-min test and standing metabolic rate (W) were assessed from the steady-state \(V_O^2\) and \(V_C^2\) using Brockett’s standard equation (3). Gross metabolic rate (W) was divided by walking speed (m/s) and then by BM and BM0.67 to obtain normalized net metabolic cost expressed in J/kg.

\[
W = \frac{m \times V}{m \times g \times h}
\]

where \(m\) is the body mass (kg) and \(V\) is the resultant COM velocity (m/s) determined from its vertical, forward, and M-L components.

Potential energy (\(E_p\); in J) of the COM was calculated as follows:

\[
E_p = \frac{1}{2} m \times V^2
\]

where \(m\) is the gravitational constant and \(h\) is the vertical position of the COM relative to heelstrike, calculated by integration of the vertical velocity. The total mechanical energy of the COM (\(E_{tot}\); in J) was computed as the sum of the \(E_{k}\) and \(E_{p}\) curves over the mean stride. \(W_{net} (J \cdot kg^{-1} \cdot m^{-1})\) was calculated as the sum of the positive increments in \(E_{tot}\), divided by step length and BM. Indeed, when walking in dynamically similar fashion, forces are proportional to body weight, and thus the mechanical cost of walking normalized by BM (J \cdot kg^{-1} \cdot m^{-1}) is independent of BM (1). Moreover, in normal-weight subjects, Schepens et al. (33) pointed out that normalized \(W_{net}\) is independent of BM since beyond the age of 10 yr subjects walk in a dynamically similar fashion.

The inverted pendulum recovery of mechanical energy of the COM was calculated according to Schepens et al. (33) as follows:

\[
\text{Recovery} = 100 \times \frac{W_k + W_p - W_{ext}}{W_k + W_p}
\]

where \(W_k\) (J) and \(W_p\) (J) are the sum of the positive increments in \(E_k\) and \(E_p\), respectively. Mechanical efficiency was calculated as the ratio of \(W_{ext}\) to \(C_w\) (both expressed in J/m).

The M-L COM displacement was equal to the total amplitude (from left to right) of the M-L COM position computed by integration of the M-L velocity over the mean stride.

**Statistical Analysis**

Mean values and standard deviations (SD) were calculated for each variable. Normal distribution of the data was checked by the Shapiro-Wilk normality test. Variance homogeneity between samples was tested by the F-Snedecor test. A two-way (speed \(
\times\) group) ANOVA with repeated measures was used to determine the effects of obesity (\(F_{obesity}\)) and speed on metabolic and mechanical parameters. If an interaction or an effect of one of the two factors was significant, a one-way ANOVA was performed. Significant ANOVA results were followed by post hoc comparisons using Newman-Keuls post hoc test. Pearson’s \(r\) correlation coefficients were used to test the association between variables of interest for the entire sample (\(n = 33\). The relationships between the different factors were demonstrated with scatter plots and linear regression analysis. Criterion for statistical significance was set at \(P < 0.05\).
RESULTS

Obese subjects presented a 30% greater standing metabolic rate (W), but, when normalized by BM, standing metabolic rate (W/kg) was 40% lower in obese than in normal-weight subjects (Table 1; *P < 0.01). All subjects matched the designated speed for each trial, and net $C_{W\cdot BM^{-1}}$ was significantly higher in obese than in normal-weight subjects by 25% on average across speeds (Table 2; $F_{obesity} = 14.14; P < 0.01$). As a consequence of the lower standing metabolic rate and the higher net $C_{W\cdot BM^{-1}}$ in obese subjects, gross $C_{W\cdot BM^{-1}}$ was not significantly different between obese and normal-weight subjects, whatever the speed (Fig. 1F; $F_{obesity} = 3.07; P = 0.09$). However, when gross $C_{W}$ was normalized by BM$^{0.67}$, gross $C_{W\cdot BM^{-1}}$ was significantly higher in obese than in normal-weight subjects ($F_{obesity} = 20.88; P < 0.01$) by 21% on average across speeds, and the variance in percent body fat explained a significant portion of the variance in gross $C_{W\cdot BM^{-1}}$ ($r^2$ ranging from 0.13 to 0.25; *P < 0.05).

Net $C_{W\cdot BM^{-1}}$ was much higher in obese than in normal-weight subjects ($F_{obesity} = 49.2; P < 0.01$) by 64% on average across speeds. Differences in net $C_{W\cdot BM^{-1}}$ ranged from 81 to 50% for walking speeds ranging from 0.75 to 1.5 m/s, respectively, yet with no significant interaction effect of walking speed (Fig. 1A). There was no difference in $W_{ext}$ (J·kg$^{-1}$·m$^{-1}$) between obese and normal-weight subjects (Fig. 1B). This difference in net $C_{W\cdot BM^{-1}}$, combined with the similar $W_{ext}$ between obese and normal-weight subjects, resulted in a significant 23% lower mechanical efficiency in obese subjects, on average across speeds (Fig. 1C; $F_{obesity} = 5.3; P < 0.05$). Note that post hoc tests showed only significant differences at the slowest speeds (Fig. 1C).

The total kinetic and potential energy fluctuations required to the recovery of mechanical energy calculation are presented in Table 3. Recovery of mechanical energy was not significantly different between obese and normal-weight subjects (Fig. 1D). As presented in Fig. 1E, M-L COM displacement was about two times greater in obese than in normal-weight subjects ($F_{obesity} = 49.9; P < 0.01$), and the two-way ANOVA showed a significant interaction effect ($F_{obesity\times speed} = 10.6; P < 0.01$) due to a larger increase in M-L COM displacement at the slowest speed compared with faster speeds in obese vs. normal-weight subjects.

When obese boys and girls were analyzed separately, mechanical and metabolic parameters did not differ significantly across speeds whatever the normalization used (e.g., $C_{W\cdot BM^{-1}}$; $F_{sex} = 3.04; P = 0.09$). Similarly, body composition did not differ significantly between obese boys and girls (e.g., percent body fat was 44 and 40% for girls and boys, respectively; *P = 0.09).

Linear regression of the pooled set of data revealed for all speeds, that the variance in percent body fat explained a significant portion of the variance in net $C_{W\cdot BM^{-1}}$ (Fig. 2A; $r^2$ ranging from 0.43 to 0.49; *P < 0.01), but, when analyzing obese and normal-weight subjects separately, the variance in percent body fat did not explain the variance in $C_{W\cdot BM^{-1}}$ in either group. The variance in percent body fat explained a significant portion of the variance in M-L COM displacement (Fig. 2C; $r^2$ ranging from 0.60 to 0.67; *P < 0.01) but did not explain the variance in $W_{ext}$ at any speed (Fig. 2B; $r^2 < 0.02; P > 0.57$). Thus subjects with greater percent body fat exhibited a greater M-L COM displacement, along with greater net $C_{W\cdot BM^{-1}}$, but for similar amounts of $W_{ext}$, Furthermore, as shown in Fig. 3A, the variance in $W_{ext}$ did not explain the variance in net $C_{W\cdot BM^{-1}}$ at any speed ($r^2 < 0.05; P > 0.23$), but the variance in M-L COM did (Fig. 3B; $r^2$ ranging from 0.42 to 0.61; *P < 0.01).

DISCUSSION

As hypothesized, $C_{W\cdot BM^{-1}}$ and $C_{W\cdot BM^{-1}}$ were significantly higher in obese subjects than in normal-weight subjects. The gross metabolic rate values (W) of our obese subjects were similar to those reported by Lazzer et al. (21) for similar BM and composition. They reported mean gross metabolic rate values of 423 and 529 W at 1.1 and 1.4 m/s, respectively, and interpolating our results to 1.1 and 1.4 m/s, we estimated our obese subjects’ mean gross metabolic rate values to be ~403 and ~502 W, respectively. In our normal-weight subjects, mean values of net $C_{W\cdot BM^{-1}}$ or net metabolic rate (W/kg) were in agreement with those of DeJaeger et al. (11) and Schepens et al. (33) obtained in 11- to 12-yr-old normal-weight subjects. For example, DeJaeger et al. (11) reported a mean value of net $C_{W}$ of 2.0 J·kg$^{-1}$·m$^{-1}$ at 1 m/s, which is close to the 2.1 J·kg$^{-1}$·m$^{-1}$ measured in the present study at the same speed.

The net $C_{W\cdot BM^{-1}}$ was significantly higher in obese than in normal-weight subjects by 25% on average across speeds, which is higher than the 10% difference in net $C_{W\cdot BM^{-1}}$ reported in adults (4, 6). However, our obese subjects had lower standing metabolic rates (W/kg), which accounted for there being no significant difference in gross $C_{W\cdot BM^{-1}}$ between obese and normal-weight subjects. Zakeri et al. (42) showed in adolescents with different body size and mass that the scaling exponent of BM for the normalization of gross $C_{W}$ was different according to their weight status (0.66 and 0.74 for normal-weight and overweight subjects, respectively), indicating a contribution of body fat mass to gross $C_{W}$. In our study, when gross $C_{W}$ was normalized by BM$^{0.67}$ ($C_{W\cdot BM^{-1}}$), it was 21% higher in obese than in normal-weight subjects, showing the relevance of the normalization to remove the effect of BM due to body size and gender and thus isolate the effect of obesity (percent body fat). As a consequence, we assumed that this higher $C_{W\cdot BM^{-1}}$ in obese subjects could be due to their higher percent body fat, which is also supported by the significant correlation found between percent body fat and gross $C_{W\cdot BM^{-1}}$ ($r^2 = 0.25$ at 1.25 m/s; *P < 0.01).

Net $C_{W\cdot BM^{-1}}$ was significantly higher in obese than in normal-weight subjects (by 64% on average across speeds), which is higher than the 25% observed in net $C_{W\cdot BM^{-1}}$. This

Table 2. Metabolic cost vs. walking speed for obese and normal-weight subjects

<table>
<thead>
<tr>
<th>Speed, m/s</th>
<th>Net Metabolic Cost, J/m</th>
<th>Net Normalized Metabolic Cost, J·kg$^{-1}$·m$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obese</td>
<td>Normal weight</td>
</tr>
<tr>
<td>0.75</td>
<td>257.1 ± 84.4†</td>
<td>82.1 ± 25.5</td>
</tr>
<tr>
<td>1.0</td>
<td>253.4 ± 89.5†</td>
<td>87.9 ± 27.7</td>
</tr>
<tr>
<td>1.25</td>
<td>262.8 ± 99.0†</td>
<td>96.1 ± 36.4</td>
</tr>
<tr>
<td>1.5</td>
<td>258.7 ± 79.4†</td>
<td>111.7 ± 28.2</td>
</tr>
</tbody>
</table>

Values are means ± SD. Significant differences between obese and normal-weight subjects: *P < 0.05; †P < 0.01.
discrepancy was due to the normalization by BM$^{0.67}$ (J·kg$^{-0.67}$·m$^{-1}$) in our study, which attributed less importance to the greater BM of obese, thus amplifying the differences in net $C_{W\cdot BM^{-0.67}}$ between the two groups. Furthermore, although this normalization seems mathematically more appropriate (7, 42), the physiological or biomechanical explanations of this normalization by BM$^{0.67}$ is still debated (1, 31).

This difference in net $C_{W\cdot BM^{-0.67}}$ was related to body composition of the subjects since the variance in percent body fat explained 46% of the variance in net $C_{W\cdot BM^{-0.67}}$. This result is in agreement with those of Browning et al. (4) in adult subjects ($r^2 = 0.45$). However, in our study, the variance in net $C_{W\cdot BM^{-0.67}}$ cannot be totally attributed to the lower standing metabolic rate decrease caused by the increase in fat mass, because gross $C_{W\cdot BM^{-0.67}}$ was also slightly related to percent body fat ($r^2 = 0.25$ at 1.25 m/s; $P < 0.01$). Consequently, in obese adolescents, the increase in net $C_{W\cdot BM^{-0.67}}$ with increasing percent fat mass must be explained by other factors.

Regarding mechanical factors, our values of $W_{ext}$ and recovery of mechanical energy in normal-weight subjects were in agreement with those of Schepens et al. (33) in 11- to 12-year-old normal-weight subjects. These factors for obese subjects, as well as M-L COM displacement for both groups, could not be compared with other studies since no such data are available to our knowledge. As hypothesized, M-L COM displacement was twice as great in obese as in normal-weight subjects. Moreover, the variance in percent body fat explained 64% of the variance in M-L COM displacement, likely due to the excessive amount of adipose tissue in the thighs, which could compel obese subjects to walk with greater step widths. However, contrary to what was hypothesized, despite M-L COM displacement being greater in obese than in normal-weight subjects, $W_{ext}$ (J·kg$^{-1}$·m$^{-1}$) was similar between the two groups, and the variance in percent body fat did not explain the variance in $W_{ext}$. Our most likely explanation is that, although M-L kinetic energy fluctuations were three times greater in obese subjects, they accounted for only 3 and 10% of the total kinetic energy fluctuations in normal-weight and obese subjects, respectively. Moreover, obese and normal-weight subjects conserved the same percentage of COM mechanical energy by inverted pendulum energy exchange despite the greater M-L COM displacement in obese subjects. The recovery of mechanical energy was calculated from the 3D (vertical, forward, and M-L) kinetic energy fluctuations, and the greater M-L COM displacement induced a greater amount of kinetic energy available to convert into gravitational potential energy, as shown during penguin walking by Griffin and Kram (18). This greater M-L COM displacement could be considered mechanically inexpensive because it did not induce an increase in $W_{ext}$.

Table 3. Total kinetic and potential energy fluctuations vs. walking speed for obese and normal-weight subjects

<table>
<thead>
<tr>
<th>Speed, m/s</th>
<th>Total Kinetic Energy Fluctuations, J·kg$^{-1}$·m$^{-1}$</th>
<th>Potential Energy Fluctuations, J·kg$^{-1}$·m$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obese</td>
<td>Normal weight</td>
</tr>
<tr>
<td>0.75</td>
<td>0.479±0.075$^*$</td>
<td>0.412±0.060</td>
</tr>
<tr>
<td>1.0</td>
<td>0.578±0.085</td>
<td>0.550±0.056</td>
</tr>
<tr>
<td>1.25</td>
<td>0.647±0.094</td>
<td>0.641±0.045</td>
</tr>
<tr>
<td>1.5</td>
<td>0.744±0.128</td>
<td>0.759±0.073</td>
</tr>
</tbody>
</table>

Values are means ± SD. $^*$Significant differences between obese and normal-weight subjects ($P < 0.05$).
who reported greater M-L GRF over longer stance time generated by obese subjects’ greater step width. Thus we can presume the greater M-L COM displacement observed in our study to be generated by greater step width. Donelan et al. (12) have shown both theoretically and experimentally that, in normal-weight subjects, the rate of mechanical work and net metabolic rate (W/kg) increased with the square of step width values above the preferred width. However, in their study, the mechanical work was assessed by the “individual limbs method” (13), which quantifies, in addition to \( W_{\text{ext}} \), an internal mechanical work performed during the double contact phase (\( W_{\text{int,dc}} \)).

During walking, the total mechanical work is the sum of \( W_{\text{ext}} \) and an internal work (\( W_{\text{int}} \)) that does not directly come from the COM movements. Only a certain amount of this \( W_{\text{int}} \) can be measured through 1) the work done to accelerate the limbs relative to the COM and 2) \( W_{\text{int,dc}} \) performed by the lower limbs when the back leg recovers the energy absorbed by the braking front leg during the double contact period, which generates forces produced by one lower limb against the other. The latter phenomenon is necessary to redirect the COM velocity from one pendular arc to the next one, and thus maintain a constant walking speed (13). This \( W_{\text{int,dc}} \) is not accounted for by the traditional combined limbs measurement of \( W_{\text{ext}} \) used in this study (8) because it only takes into account the net (sum of positive and negative) work done by the lower limbs during the double contact phase.

Last and more importantly, Donelan et al. (12) reported 1) that greater step widths generated an increase in \( W_{\text{int,dc}} \) without change in \( W_{\text{ext}} \) and 2) that this increase in \( W_{\text{int,dc}} \)

\[ \text{(J·kg}^{-1}·\text{m}^{-1}) \]. There was no significant correlation between \( W_{\text{ext}} \) and \( C_{W\cdotBM} \) or between percent body fat and \( W_{\text{ext}} \). Consequently, the higher net \( C_{W\cdotBM} \) in obese subjects was not due to a higher \( W_{\text{ext}} \). Based on our values for \( W_{\text{ext}} \), one can assume that similar muscular work was performed to lift and accelerate the COM by both obese and normal-weight subjects, but greater net \( C_{W\cdotBM} \) was expended by the obese subjects. As a result, mechanical efficiency was greater in normal-weight than in obese subjects. However, it may be premature to conclude that muscular efficiency was impaired, because the mechanical work has been only partially quantified.

Surprisingly, the variance in M-L COM displacement explained on average 49% of the variance in net \( C_{W\cdotBM} \), but this relationship could be explained neither by \( W_{\text{ext}} \) nor by the recovery of mechanical energy (both parameters being similar between the two groups). An explanation could be that greater M-L COM displacement may have induced modifications of the walking pattern that were not (or not accurately enough) quantified through our measurement of \( W_{\text{ext}} \). This hypothesis is supported by the results of the study of Browning and Kram (5)
induced a proportional increase in net metabolic rate. Thus, when our data are considered, obese subjects walking with greater step width (as revealed by the greater M-L COM displacement) could have produced higher $W_{\text{ext},dc}$ due to higher forces produced by one lower limb against the other during the double contact phase. Therefore, higher muscle forces could require an additional metabolic energy (hence a higher net $C_{W,BM^{-\alpha \tau}}$) with no parallel increase in $W_{\text{ext}}$. This possibility is supported by the significant correlation found between M-L COM displacement and net $C_{W,BM^{-\alpha \tau}}$, as well as by the lack of differences in $W_{\text{ext}}$ observed between obese and normal-weight subjects.

This greater M-L COM displacement and the wider step width in obese subjects (5) could also be due to the reduced postural stability observed in this population (25). Donelan et al. (14) have shown in normal-weight subjects that body lateral motion was partially stabilized via medio-lateral foot placement, and thus lateral instability could affect the choice of the preferred step width. In their study, external stabilization induced a decrease in preferred step width and a concomitant lower cost of the step-to-step transition, resulting in a 6% decrease in net metabolic rate (W/kg). Our results showed that percent body fat had more of an effect on M-L COM displacement at slow speeds (Figs. 1E and 2C show greater slopes at the slowest speeds). This could be due in obese subjects to a decrease in lateral stability with the decreasing speed, requiring a greater step width and thus a greater M-L COM displacement. The wider step and M-L COM displacement accompanied by higher muscle activations (14) could have induced the higher net $C_{W,BM^{-\alpha \tau}}$ observed at slow speeds, which could be supported by the greater slopes at the slowest speeds observed in the $C_{W,BM^{-\alpha \tau}}$-percent body fat relationships (Fig. 2A). Moreover, walking with a wider step width and heavier legs could also induce a higher cost of the lateral leg swing circumduction (35), which could partly explain the higher net $C_{W,BM^{-\alpha \tau}}$ in obese subjects.

Field measurement with an inertial/gyroscope sensor was performed to accurately investigate obese adolescents natural walking but presented some limitations. Indeed, in the present study, external stabilization induced a decrease in preferred step width and a concomitant lower cost of the step-to-step transition, resulting in a 6% decrease in net metabolic rate (W/kg). Our results showed that percent body fat had more of an effect on M-L COM displacement at slow speeds (Figs. 1E and 2C show greater slopes at the slowest speeds). This could be due in obese subjects to a decrease in lateral stability with the decreasing speed, requiring a greater step width and thus a greater M-L COM displacement. The wider step and M-L COM displacement accompanied by higher muscle activations (14) could have induced the higher net $C_{W,BM^{-\alpha \tau}}$ observed at slow speeds, which could be supported by the greater slopes at the slowest speeds observed in the $C_{W,BM^{-\alpha \tau}}$-percent body fat relationships (Fig. 2A). Moreover, walking with a wider step width and heavier legs could also induce a higher cost of the lateral leg swing circumduction (35), which could partly explain the higher net $C_{W,BM^{-\alpha \tau}}$ in obese subjects.

Field measurement with an inertial/gyroscope sensor was performed to accurately investigate obese adolescents natural walking but presented some limitations. Indeed, in the present study, $W_{\text{ext},dc}$ could not be calculated because we used this measurement method. Moreover, in the validation study of Meichtry et al. (26), the authors noticed an overestimation of $W_{\text{ext}}$ (J·kg$^{-1}$·m$^{-1}$) and 3D displacements. This fact could be due to the level and the attachment type of the sensor and to the uncorrected instantaneous sensor orientation. As recommended by these authors, in the present study, a tri-axial accelerometer equipped with a gyroscope was used to reposition the 3D accelerations in the earth reference system. Moreover, the sensor was firmly taped with a wide adhesive strap to limit the sensor movement associated with the skin movements (and underlying tissue) as much as possible.

In conclusion, we found that, in natural walking conditions, net metabolic cost of walking (normalized by either BM$^{0.67}$ or BM) was greater in obese adolescents and related to the percent body fat of the subjects. We observed significant changes in the mechanical walking pattern in obese compared with normal-weight subjects, in particular a greater mediolateral center of mass displacement associated with greater step widths. This greater mediolateral center of mass displacement did not correspond with greater external mechanical work as measured in this study. However, the greater net metabolic cost of walking in obese subjects may be partially explained by the increased step-to-step transition cost (i.e., the internal work occurring during the double contact phase) associated with wide gait. Therefore, future studies are needed to understand whether the greater net metabolic cost of walking by obese individuals is a result of their greater step widths and an associated increase in individual limb work during the double contact phase.

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