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RESEARCH ARTICLE

Mass-normalized internal mechanical work in walking is not impaired in adults with class III obesity

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Fernández Menéndez A, Uva B, Favre L, Hans D, Borrani F, Malatesta D. Mass-normalized internal mechanical work in walking is not impaired in adults with class III obesity. *J Appl Physiol* 129: 194–203, 2020. First published June 25, 2020; doi:10.1152/japplphysiol.00837.2019.—This study aimed to investigate the effects of obesity on the internal mechanical work, and its influence on the total mechanical work, energy cost, and mechanical efficiency in obese and nonobese adults while walking at different speeds. Body composition and anthropometrical characteristics were obtained for eleven obese [O; 39.9 ± 7.9 yr; body mass index (BMI): 43.0 ± 4.2 kg/m^2] and thirteen lean adults (L; 29.6 ± 5.7 yr; BMI: 22.0 ± 1.5 kg/m^2). Participants walked at five speeds (0.56, 0.83, 1.11, 1.39, 1.67 m/s) while oxygen consumption was measured to obtain net energy cost of walking (NC$_w$). A motion analysis system and instrumented treadmill were combined to obtain external (W$_{ext}$), internal (W$_{int}$), and total (W$_{tot}$) mechanical work, and pendular energy recovery. Mechanical efficiency was calculated as the ratio of W$_{tot}$ to NC$_w$. Relative NC$_w$ (per unit body mass) was significantly higher in O than L ($P \leq 0.001$). Relative W$_{ext}$ was significantly lower in O compared with L ($P = 0.002$), whereas no significant difference was found in relative W$_{int}$ ($P = 0.16$) and W$_{tot}$ ($P = 0.6$). Recovery was significantly higher ($P \leq 0.001$), while mechanical efficiency was significantly lower in O than in L ($P \leq 0.001$). These results suggest that individuals with obesity class III have similar mass-normalized W$_{int}$ and W$_{tot}$ compared with their lean counterparts, along with a higher relative NC$_w$. Consequently, the efficiency of walking was reduced in this population. These results suggest that mass-normalized W$_{int}$ is unaffected by obesity and is not responsible for the higher relative NC$_w$ and lower efficiency of walking in these individuals.

NEW & NOTEWORTHY It has been suggested that internal mechanical work (i.e., the work required to move the limbs with respect to the center of mass, W$_{int}$) may be responsible for the higher net cost of walking in obese adults, but this variable has not yet been studied in individuals with obesity. The main finding of the present study is that individuals with class III obesity exhibit a similar amount of mass-normalized W$_{int}$ to that of adults with a normal body weight, suggesting that body mass-relative W$_{int}$ is not affected by obesity and is not responsible for the higher energy cost and the lower efficiency of walking in this population.

efficiency; energy cost; gait; locomotion; mechanical energy, obesity

INTRODUCTION

Obesity has been recognized as a significant public health issue across the globe, with a prevalence that has been continuously increasing over the past decades, leading to a variety of chronic diseases and increasing health care costs (33a). Physical activity is known to be a key strategy for preventing obesity, and one of the most common modes of physical activity is walking (33). Therefore, the characterization and analysis of the energetics and biomechanics of walking in obese individuals may provide insight into the use of walking as an exercise for weight-management protocols in this population.

It has been shown that both the absolute (J/m) and the relative (i.e., normalized by body mass, J·kg^{-1}·m^{-1}) net energy cost of walking (energy expenditure per unit distance, NC$_w$) is higher in people with obesity than in individuals with a normal body mass, suggesting that the body mass is the main factor but not the only factor decreasing economy in this population (3, 34, 35). This energy is required by the muscles to generate force and perform positive mechanical work during walking (W$_{tot}$), and one of the components of W$_{tot}$ is external mechanical work (i.e., work performed to lift and accelerate the center of mass relative to the surroundings, W$_{ext}$) (6, 7). Initially, some authors have hypothesized that the difference in NC$_w$ may be due to a higher W$_{ext}$ in obese subjects (3). However, recent studies have shown that mass-normalized W$_{ext}$ as well as the inverted pendulum mechanism (i.e., recovery), which is the mechanism that reduces W$_{ext}$ due to an exchange of kinetic energy with potential energy and vice versa, are not impaired in these individuals (4, 34, 35). Moreover, a previous study reported that at higher speeds, obese adults have a lower mass-normalized W$_{ext}$ and a higher recovery than their lean counterparts do (14). These results suggest that the internal mechanical work (i.e., work required to move the limbs with respect to the center of mass, W$_{int}$), which is the second component of W$_{tot}$ (6, 42), may be responsible for the higher cost of walking in obese adults. In fact, different studies have demonstrated that some biomechanical determinants that influence W$_{int}$ are impaired in this population, such as reduced balance (27), greater hip abduction (39), and greater step width (10, 25, 39). These impairments may be due to a larger thigh circumference causing a greater leg swing circumduction, which affects the kinematics during walking and increases the NC$_w$, as previously demonstrated in subjects with a normal

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body weight (38). Moreover, compared with lean adults, the difference in the mass distribution, caused by the disproportional increase in the lower limb mass (especially thigh) respect to total body mass in obese individuals, has been suggested to mainly affect W_{int} per unit of mass independently of the body mass (32, 37). However, the calculation of W_{int} and its influence on the energetics of walking in obese individuals has not been extensively studied. Traditionally, W_{int} is obtained by motion capture data from passive reflective markers and assumptions of different physical properties of the body segments that can differ substantially between individuals of a normal body weight and individuals with obesity, particularly those with class II and III obesity (13). Moreover, this methodology can be very sensitive to marker placement errors and soft tissue artifacts in this population, which may lead to gross errors in the biomechanical measurements (23). Therefore, a new approach, that considers the interindividual differences and the errors due to soft tissue excess, is needed to properly quantify W_{int} in these individuals and provide a more complete evaluation of the efficiency of walking and how metabolic energy is transformed into W_{tot} in this population. To the best of our knowledge, neither W_{tot} nor the efficiency of mechanical work production during walking has been studied in obese adults.

Hence, the purpose of this study was to investigate the effects of obesity on internal mechanical work and the influence of obesity on total mechanical work, energy cost, and mechanical efficiency in obese (class III) and nonobese adults while walking at different speeds. The hypothesis was that, when normalized by the body mass, NC_w and W_{tot} are higher in obese than in nonobese individuals, mainly due to the greater W_{int} required to move a unit of mass in obese adults with a similar W_{ext} between groups, resulting in a similar level of mechanical efficiency during walking between groups.

METHODS

Participants

Eleven sedentary, obese adults [O; body mass index (BMI): 42.95 ± 4.2 kg/m^2; ≤2 h of physical activity per week over the past year] and thirteen lean adults (L; BMI: 22.02 ± 1.5 kg/m^2) were recruited to participate in this study (Table 1). All participants were healthy and free of musculoskeletal injuries and cardiovascular and respiratory diseases that could affect their gait pattern. The study was approved by the local ethics committee (CER-VD 2016–01715), and all the subjects provided written informed consent.

Experimental Design

Prior to testing, each obese participant underwent a dual-energy X-ray absorptiometry scan (iDXA; GE Healthcare Lunar) to obtain the anthropometrical characteristics and body composition. Then, the participants were sent to the laboratory and were asked to wear tight-fitting clothing. They performed a 10-min treadmill familiarization session at the different experimental walking speeds (41). Afterwards, each individual performed 5-min walking trials at five different and equally spaced speeds (0.56, 0.83, 1.11, 1.39, 1.67 m/s) on an instrumented, single-belt treadmill (T150–FMT–MED, Arsalis, Belgium) with 5 min of rest between each walking speed. Participants were asked to complete the walking trials without using the handrail support. The order of the speeds was determined randomly. During each walking trial, metabolic and mechanical data were collected.

Table 1. *Physical characteristics of the participants*

Subject Characteristics	Lean Group (L)	Obese Group (O)
Sex	8 W, 5 M	9 W, 2 M
Age, yr†	29.6 ± 5.7	39.9 ± 7.9
Height, m†	1.71 ± 0.1	1.65 ± 0.0
BMI, kg/m^2†	22.0 ± 1.5	43.0 ± 4.2
Body mass, kg†	64.2 ± 8.4	116.6 ± 10.3
Lower limb mass, kg†	20.7 ± 2.7	40.4 ± 6.6
Upper limb mass, kg†	6.4 ± 0.8	12.5 ± 1.4
Head and trunk mass, kg†	37.1 ± 4.8	59.8 ± 6.0
Lean body mass, kg	—	53.4 ± 5.5
Fat body mass, kg	—	59.0 ± 10.5
Fat body mass, %body mass	—	50.3 ± 5.6
Standing RMR, W/kg body mass†	1.8 ± 0.2	1.2 ± 0.1
Standing RMR, W/kg lean body mass	—	2.5 ± 0.3
Standing RMR, W/kg lower limbs mass†	5.5 ± 0.5	3.4 ± 0.6
Standing RMR, W/kg upper limbs mass†	17.6 ± 1.5	10.9 ± 1.3
Standing RMR, W/kg HAT mass†	3.0 ± 0.3	2.3 ± 0.2

Values are means ± SD. W, women; M, men; BMI, body mass index; Standing RMR, standing resting metabolic rate; HAT, head and trunk. †Significant difference ($P < 0.05$) between groups.

Assessments

Body composition and anthropometric characteristics. iDXA was used to assess total and regional body weight and composition (lean and fat mass) as well as the height and width of each anthropometric segment (hand, forearm, upper arm, foot, shank, thigh, head and trunk) for the group of obese individuals. These measurements were used to account for interindividual differences and obtain a personalized mathematical model that represents the individual's body segments as simple geometrical solids, where the dimensions, centers of mass (COMs), and inertial properties of each segment were previously described in detail by Hanavan (18).

Energy cost of walking. Prior to the walking trials, a 5-min resting measurement of the gas exchange in the standing position was collected. Volume and gas calibrations were performed before each trial. Then, breath-by-breath oxygen uptake ($\dot{V}O_2$) and CO_2 output ($\dot{V}CO_2$) were measured (Quark CPET, Cosmed, Italy) during each walking speed with a respiratory exchange ratio (RER) of less than 1 for all subjects and conditions. Breath-by-breath $\dot{V}O_2$ data were initially examined to exclude errant breaths due to coughing or swallowing, and values that were more than 3 standard deviations (SD) from the local mean were discarded. Values from the last minute were averaged to calculate the gross metabolic rate (W/kg) using the energy equivalent of O_2 (1). Then, the standing metabolic rate during resting (SMR; W/kg) was subtracted to obtain the net metabolic rate (W/kg) and divided by the corresponding walking speed to determine NC_w. NC_w is presented in this manuscript in absolute (J/m) and relative (i.e., normalized by the body mass; J·kg^{-1}·m^{-1}) values.

External mechanical work, spatiotemporal parameters, and recovery. W_{ext} was determined with an instrumented treadmill according to the methodology described in previous studies (15, 26). Twenty steps from the last 30 s of each walking trial were selected to obtain the vertical (F_v), forward (F_f), and lateral (F_l) ground reaction forces (GRF), which were measured at a sampling rate of 1,000 Hz. The beginning and end of each step were defined as the instant when F_f was equal to zero (15). Step length and step duration as well as double and single support phases were then determined. The GRFs were used to calculate the 3-D acceleration and the changes in the three components of velocity of the center of mass (V_v, V_f, and V_l). To exclude errant measures, steps were selected when the sum of the increments in the velocity changes did not differ by more than 25% from the sum of the decrements (7, 26). From these velocity changes and the body mass (m), the instantaneous vertical, forward, and lateral kinetic energy of the COMb (E_{kv}, E_{kf}, and E_{kl}, respectively) were obtained

(*Eq. 1*). The integration of the V_v defined the vertical position of the COMb (h), which was used, with m and gravity ($g = 9.81$ m/s^2) to obtain the instantaneous potential energy (E_p, *Eq. 2*). Total mechanical energy (E_{tot}) was calculated as the sum of the increments in E_k and E_p (*Eq. 3*).

$$E_k = E_{kh} + E_{kv} + E_{kl} = 0.5m\left(V_h^2 + V_v^2 + V_l^2\right) \quad (1)$$

$$E_p = mgh \quad (2)$$

$$E_{tot} = E_k + E_p = E_{kf} + E_{kv} + E_{kl} + E_p \quad (3)$$

Then the amount of W_{ext} performed per step was defined as the sum of the positive increments in E_{tot}. Afterwards, the recovery that quantified the percentage of mechanical energy saved via the pendulum mechanism (i.e., pendular transduction of potential into kinetic energy and vice versa) was obtained as follows (*Eq. 4*).

$$\text{Recovery}\left(\%\right) = \frac{W_k + W_p - W_{ext}}{W_k + W_p} \times 100 \quad (4)$$

where W_k and W_p represent the sum of the increments in the E_k and E_p curves, respectively.

Internal mechanical work. A motion capture system based on optical technology with a set of 8 infrared cameras (Smart-DX, BTS Bioengineering Corp., Italy) and a sampling frequency of 100 Hz was synchronized with the instrumented treadmill and used to collect kinematic and kinetic data for each step selected. Reflective markers were placed on both sides of the body over the following anatomical landmarks identified via iDXA for O and identified via palpation for L: 7th cervical vertebra, right scapular inferior angle, acromion, humerus, humeral lateral epicondyle, ulnar styloid, posterior and superior iliac spines, greater trochanter, medial and lateral epicondyles of the femur, medial and lateral malleoli, calcaneus and second metatarsal. Clusters of four noncollinear markers were positioned on the thigh, shank, and sacrum. The coordinates and trajectories of all the markers during the walking trials were recorded and computed to obtain the linear velocity of the center of mass of the *i*th segment (V_i) and its angular velocity (w_i). The translational velocity of the center of mass of the *i*th segment relative to the COMb (V_{ri}) was calculated by subtracting the absolute velocity of the COMb (obtained from the GRFs) from the V_i. The V_{ri} was then used to determine the translational kinetic energy (1st term of *Eq. 5*). The mass (m_i) and radius of gyration (k_i) of the *i*th segment were obtained from the iDXA for O and from the anthropometric tables (43) for L and used, along with w_i, to calculate rotational kinetic energy (2nd term of *Eq. 5*). The kinetic energy (Ek_{int}) due to the movements of the segments relative to the body center of mass was calculated as the sum of the translational and rotational kinetic energy for each step (*Eq. 5*):

$$Ek_{int} = \frac{1}{2}m_iV_{ri}^2 + \frac{1}{2}m_ik_i^2w_i^2 \quad (5)$$

To minimize errors due to noise in the signals, the Ek_{int} signal was low pass filtered with a fourth-order zero-lag Butterworth filter and a cutoff frequency of 7 Hz. Points identified as outliers were corrected using a spline interpolation method. To account for the energy transfer between segments, the Ek_{int} curves of the segments of the same limb were summed. W_{int} values for the lower limbs, upper limbs, and both the head and the trunk ($W_{int,LL}$, $W_{int,UL}$, and $W_{int,HT}$, respectively) were defined as the sum of the increments in their respective Ek_{int} curve. $W_{int,LL}$, $W_{int,UL}$ and $W_{int,HT}$ were then summed to obtain the total W_{int} in absolute (J/m) and relative (J·kg^{-1}·m^{-1}) terms, as well as the total W_{int} normalized by the corresponding body segment mass rather than by the total body mass (i.e., lower limbs, upper limbs and head and trunk mass; $W_{int,LL}$/LLM, $W_{int,UL}$/ULM, and $W_{int,HT}$/HTM; respectively).

Total mechanical work and mechanical efficiency. The total positive mechanical work performed per distance traveled (W_{tot}) was evaluated as the sum of W_{ext} and W_{int}, assuming there was no transfer of energy between the two types of energy (42). Throughout this manuscript, all the mechanical work values are presented as both absolute (J/m) and relative (i.e., normalized by body mass, J·kg^{-1}·m^{-1}) values. Mechanical efficiency was defined as the ratio of W_{tot} to NC_w.

Statistical Analysis

Statistical analysis was performed using SPSS software version 25 (IBM, Armonk, NY). A *t*-test was used to compare the anthropometric variables between O and L. The mechanics and energetics of walking at 5 fixed speeds were evaluated with a linear mixed effects analysis of the relationships between conditions [walking speed (0.56, 0.83, 1.11, 1.39, 1.67 m/s)] and group (O vs. L)]. The fixed effects included walking speed and group, while participant was set as a random effect. The normality of the residuals was tested using the Kolmogorov-Smirnov test. To better understand the mechanisms related to NC_w, we performed Spearman's correlation analyses between the mechanical variables and NC_w. Because it is well accepted that speed influences metabolic and mechanical variables, the main effects of speed are not reported in this article. The level of significance was set to $P \leq 0.05$, and the level of tendency was set to $P \leq 0.1$. All the values are reported as means ± standard deviation (SD).

RESULTS

Participant Characteristics

The anthropometric values of the two groups are presented in Table 1. A significant difference in age was found between groups with a higher value for O than for L ($P = 0.003$). Body mass, as well as shank mass, thigh mass, and total lower limb mass ($P \leq 0.001$), was significantly higher in O than in L ($P \leq 0.001$). However, no significant difference was found in foot mass between the two groups ($P = 0.73$; data not shown). Height was significantly lower in O than in L ($P = 0.048$), and a trend showing shorter lower limbs for O than for L was found (0.86 ± 0.0 m and 0.90 ± 0.1 m, respectively; $P = 0.064$). The anthropometrical characteristics of both groups are presented in Table 2.

Energetics

The SMR was significantly higher in L than in O ($P \leq 0.001$; Table 1). Absolute NC_w was significantly higher in O than in L ($P \leq 0.001$), with a significant speed × group interaction ($P \leq 0.001$) and higher values found in O than in L for all the walking speeds ($P \leq 0.001$; Fig. 1*A*). A significant effect of group was found for the relative NC_w, with higher values observed in O than in L ($P \leq 0.001$). A significant speed × group interaction was also found ($P \leq 0.001$) for this variable, with significantly higher values in O than in L at all the walking speeds ($P \leq 0.003$; Fig. 1*B*).

Mechanics

Spatiotemporal parameters. Step length and duration were significantly lower in O than in L ($P \leq 0.001$). However, a significant speed × group interaction was only found in step duration ($P = 0.005$), with significantly lower values in O than in L only at the slowest speeds (0.56 and 0.83 m/s; $P \leq 0.001$ and $P = 0.03$, respectively; Table 3). There was no significant difference in double support time between groups ($P = 0.46$; Table 3), but the single support phase was significantly shorter

Table 2. *Body segment parameters of the participants*

Segments	Weight, kg		Length, m		COM_s Prox/Segment Length		Radius of Gyration/Segment Length	
	Lean	Obese	Lean	Obese	Lean	Obese	Lean	Obese
Hand	0.39 ± 0.1	0.40 ± 0.1	0.18 ± 0.0	0.16 ± 0.0	0.51 ± 0.0	0.50 ± 0.0	0.30 ± 0.0	0.32 ± 0.0
Forearm	1.03 ± 0.1	1.41 ± 0.2	0.25 ± 0.0	0.24 ± 0.0	0.43 ± 0.0	0.39 ± 0.0	0.30 ± 0.0	0.29 ± 0.0
Upper arm	1.80 ± 0.2	4.6 ± 0.6	0.32 ± 0.0	0.27 ± 0.0	0.44 ± 0.0	0.47 ± 0.0	0.32 ± 0.0	0.32 ± 0.0
Foot	0.93 ± 0.1	0.96 ± 0.2	0.26 ± 0.0	0.25 ± 0.0	0.50 ± 0.0	0.44 ± 0.0	0.48 ± 0.0	0.29 ± 0.0
Shank	2.99 ± 0.4	4.61 ± 1.0	0.42 ± 0.0	0.36 ± 0.0	0.43 ± 0.0	0.39 ± 0.0	0.30 ± 0.0	0.29 ± 0.0
Thigh	6.42 ± 0.8	15.73 ± 2.4	0.42 ± 0.0	0.41 ± 0.0	0.43 ± 0.0	0.42 ± 0.0	0.32 ± 0.0	0.31 ± 0.0
Trunk	31.91 ± 4.2	54.60 ± 5.9	0.49 ± 0.0	0.57 ± 0.0	0.50 ± 0.0	0.42 ± 0.0	0.50 ± 0.0	0.33 ± 0.0
Head	5.20 ± 0.7	5.17 ± 0.6	0.22 ± 0.0	0.23 ± 0.0	0.50 ± 0.0	0.50 ± 0.0	0.50 ± 0.0	0.32 ± 0.0

Values are means ± SD. COM_s Prox/Segment Length, position of the center of mass of each segment as a percent of segment length from the proximal end.

in O than in L ($P \leq 0.001$), with significantly lower durations at 0.56, 0.83, 1.11, and 1.39 m/s ($P < 0.02$; Table 3).

External mechanical work. The absolute W_{ext} was significantly higher in O than in L ($P \leq 0.001$), and a trend toward a speed × group interaction was found for this variable ($P = 0.09$; Fig. 2*A*). However, the relative W_{ext} was significantly lower in O than in L ($P = 0.002$), with significantly lower values in the former than in the latter at 1.11, 1.39, and 1.67 m/s ($P \leq 0.04$; Fig. 2*B*).

Internal mechanical work. The absolute W_{int} of the O group was significantly higher than that of the L group ($P \leq 0.001$). No significant speed × group interaction was found for this variable ($P = 0.12$; Fig. 2*C*). The body mass-relative W_{int} values of the two groups were similar ($P = 0.16$), and there was no speed × group interaction ($P = 0.42$; Fig. 2*D*). The absolute $W_{int,LL}$, $W_{int,UL}$, and $W_{int,HT}$ were significantly higher in O than in L ($P \leq 0.001$ for all; Fig. 2*E*). A significant speed × group interaction was only found in $W_{int,LL}$ ($P \leq 0.001$), with higher values in O than in L for all the walking speeds ($P \leq 0.001$; Fig. 2*E*). A trend toward a lower relative $W_{int,LL}$ of O than that of L was found ($P = 0.06$; Fig. 2*F*), while relative $W_{int,UL}$ and $W_{int,HT}$ were significantly higher in O than in L ($P = 0.011$ and $P = 0.013$, respectively; Fig. 2*F*), and no significant speed × group interactions were observed for these variables ($P \geq 0.33$). The relative translational $W_{int,LL}$ was significantly lower in O than in L ($P = 0.04$; Fig. 3*A*), while the relative translational $W_{int,UL}$ and $W_{int,HT}$ were significantly higher in O than in L ($P = 0.012$ and $P \leq 0.001$, Fig. 3, *B* and *C*, respectively). No differences were found in the relative rotational $W_{int,LL}$ between groups ($P = 0.73$; Fig. 3*D*), but a significantly higher relative rotational $W_{int,UL}$ was found in O compared with that of L ($P = 0.01$; Fig. 3*E*), along with significantly lower values in relative rotational $W_{int,HT}$ in O compared with those of L ($P \leq 0.001$; Fig. 3*F*). No significant speed × group interaction was found for these variables ($P > 0.15$). Spearman's rank correlation analysis showed that relative $W_{int,UL}$ and $W_{int,HT}$ are inversely correlated to relative NC_w at 0.56 m/s ($r = -0.64$, $P = 0.035$ and $r = -0.78$, $P = 0.005$, respectively).

The percentage of relative W_{int} that corresponds to $W_{int,LL}$ was significantly lower in O than in L ($P \leq 0.001$). However, the percentages that corresponded to $W_{int,UL}$ and $W_{int,HT}$ were significantly higher in O than in L ($P \leq 0.004$; Fig. 4*A*), with no speed × group interaction detected.

When the W_{int} of each segment (i.e., $W_{int,LL}$, $W_{int,UL}$, and $W_{int,HT}$) was normalized by its corresponding body segment mass, $W_{int,LL}$/LLM was significantly different between both groups ($P \leq 0.001$), with significantly lower values in O than in L at 0.83, 1.11, 1.39, and 1.67 m/s ($P \leq 0.001$; Fig. 4*B*). No significant difference between groups was found in $W_{int,UL}$/ULM (Fig. 4*B*). $W_{int,HT}$/HTM was significantly higher in O than in L ($P \leq 0.001$, Fig. 4*B*), and no significant speed × group interaction was observed.

Total mechanical work. The O group walked with a significantly higher absolute W_{tot} than did the L group ($P \leq 0.001$), and a tendency was found in the speed × group interaction ($P = 0.08$; Fig. 2*G*). The amount of relative W_{tot} was similar between the two groups ($P = 0.60$), while a significant speed × group interaction was found ($P = 0.008$) with significantly higher values in O than in L at 0.56 m/s ($P = 0.007$), but there was a tendency of lower values in the former than in the latter at 1.39 m/s ($P = 0.09$; Fig. 2*H*). The contribution of the W_{ext} to the W_{tot} was significantly lower in O than in L (averaged values across all speeds: 49.8% and 52.4%, respectively; $P = 0.006$), while W_{int} contributed significantly more to the W_{tot} in O than in L (averaged values across all speeds: 50.2% and 47.6%, respectively; $P = 0.006$).

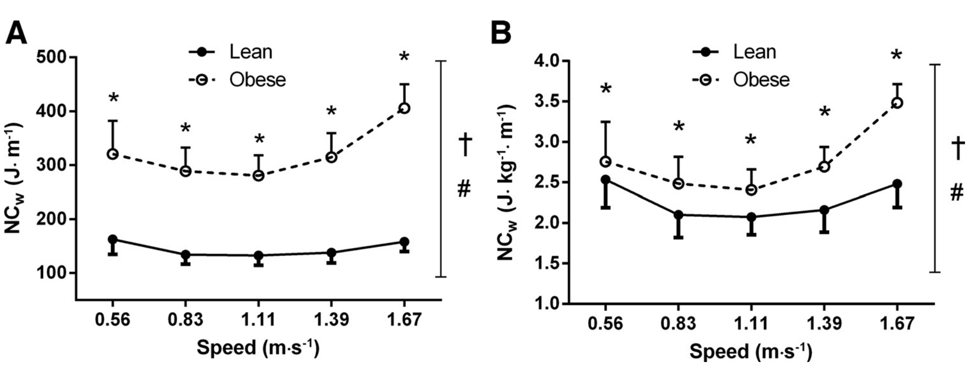


Fig. 1. Absolute net energy cost of walking [NC_w (J/m)] (*A*) and relative net energy cost of walking [NC_w (J·kg^{-1}·m^{-1})] (*B*). The dashed lines with open circles correspond to the obese group ($n = 11$ except for 6 km/h·with $n = 6$ because 5 participants were not able to complete this walking condition) and the solid lines with black circles correspond to the lean group ($n = 13$). The values are presented as the means ± SD. †Significant difference ($P < 0.05$) between groups. #Significant speed × group interaction effect ($P < 0.05$). *Significant difference ($P < 0.05$) between the obese and the lean group for each speed.

Table 3. *Spatiotemporal parameters at the experimental walking speeds*

Variables	0.56 m/s Lean	0.56 m/s Obese	0.83 m/s Lean	0.83 m/s Obese	1.11 m/s Lean	1.11 m/s Obese	1.39 m/s Lean	1.39 m/s Obese	1.67 m/s Lean	1.67 m/s Obese
Step length, m†	0.47 ± 0.0	0.43 ± 0.1	0.56 ± 0.0	0.54 ± 0.0	0.64 ± 0.0	0.63 ± 0.0	0.73 ± 0.0	0.71 ± 0.0	0.81 ± 0.0	0.81 ± 0.0
Step duration, s†‡	0.86 ± 0.0	0.78 ± 0.1*	0.68 ± 0.1	0.65 ± 0.1*	0.59 ± 0.1	0.57 ± 0.0	0.53 ± 0.0	0.52 ± 0.0	0.49 ± 0.0	0.49 ± 0.0
Double support, s	0.31 ± 0.0	0.31 ± 0.0	0.22 ± 0.0	0.23 ± 0.0	0.18 ± 0.0	0.19 ± 0.0	0.15 ± 0.0	0.15 ± 0.0	0.13 ± 0.0	0.13 ± 0.0
Single support, s†‡	0.54 ± 0.0	0.47 ± 0.1*	0.46 ± 0.0	0.42 ± 0.0*	0.41 ± 0.0	0.39 ± 0.0*	0.38 ± 0.0	0.36 ± 0.0*	0.36 ± 0.0	0.36 ± 0.0

Values are means ± SD. †Significant difference ($P < 0.05$) between groups. ‡Significant speed × group interaction ($P < 0.05$). *Significant difference ($P < 0.05$) between the lean and the obese group for each speed.

Recovery and mechanical efficiency. Recovery was significantly higher in O than in L ($P \leq 0.001$), with no significant speed × group interaction ($P = 0.69$; Fig. 5*A*). A significant difference between groups was found in efficiency ($P \leq 0.001$). A significant speed × group interaction was found for this variable ($P \leq 0.001$), with lower values in O than in L at 0.83, 1.11, 1.39, and 1.67 m/s ($P \leq 0.005$; Fig. 5*B*).

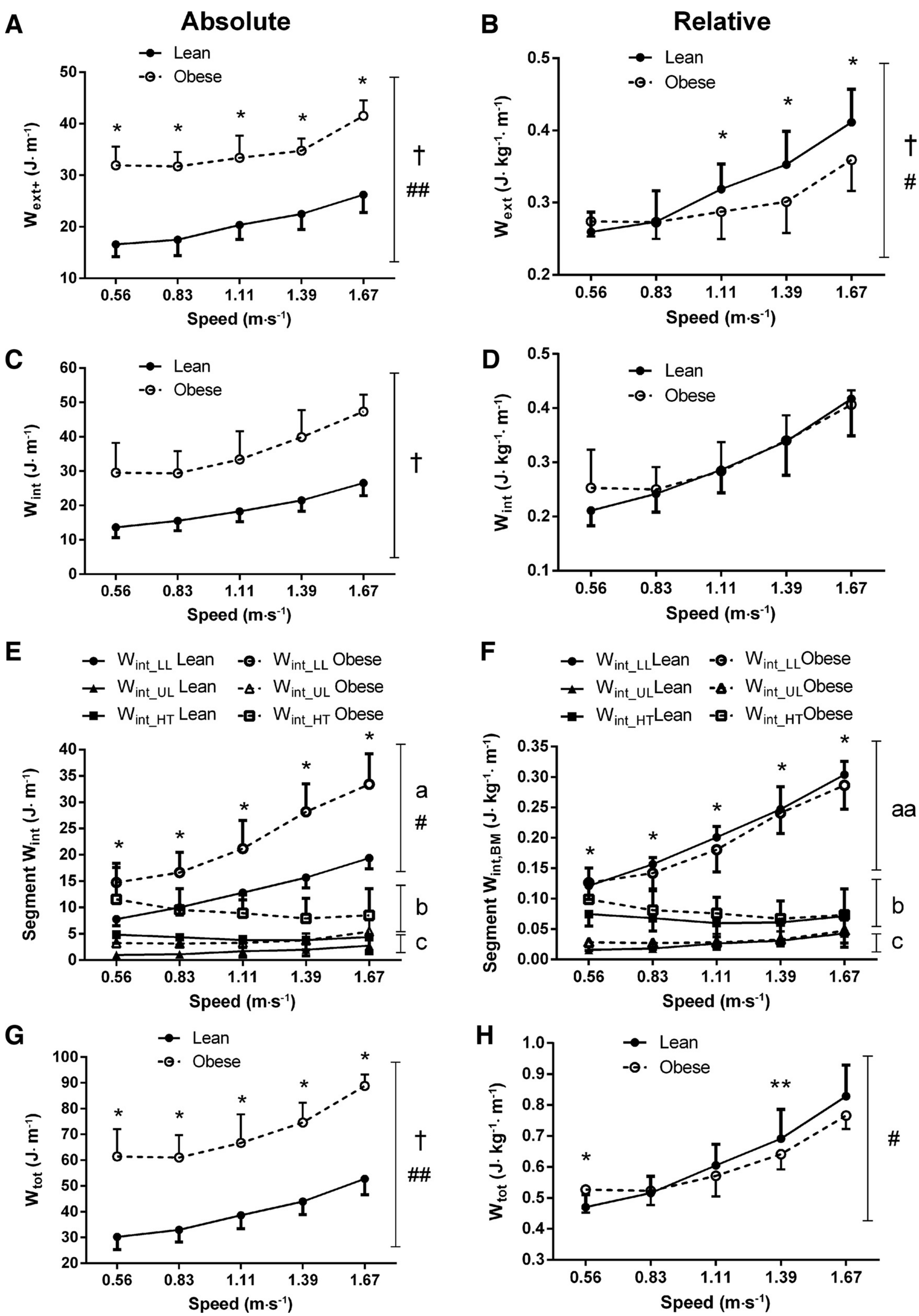
DISCUSSION

The main finding of the present study is that adults with class III obesity exhibited similar internal and total mechanical work per kilogram of body mass along with a higher relative net energy cost of walking compared with their lean counterparts. Consequently, the efficiency of walking was reduced in obese individuals. These results suggest that mass-normalized internal mechanical work is unaffected by obesity and is not responsible for the higher relative energy cost and the lower efficiency of walking observed in these individuals.

As expected, all energetic and mechanical variables were significantly higher in the obese individuals when the variables were expressed in absolute terms (J/m). However, several differences were found when the same variables were normalized by body mass ($J \cdot kg^{-1} \cdot m^{-1}$), suggesting that body mass is an important, but not the only determinant affecting the lower economy in this population. In fact, the SMR was lower in subjects with obesity than in lean individuals when it was normalized by kilograms of body mass. This result agrees with previous studies that suggest the lower SMR in individuals with obesity is due to their larger body fat percentage, and this difference can contribute to increase their NC_w compared with subjects with a normal weight (3). This was corroborated by our findings since mass-normalized NC_w was 19% higher (averaged across all the speeds tested) in obese than in lean individuals. Some recent studies have reported similar results but with a smaller difference (~10%), probably due to the lower BMI of their subjects (34 kg/m^2) (3) compared with that of the subjects in this study, suggesting that the degree of obesity may have an important impact on the energy cost of walking in individuals with obesity.

Moreover, it is well accepted that this increase in mass-normalized NC_w in individuals with obesity may also be explained by some modifications in their walking pattern that may lead to an increase in the mechanical work performed by these individuals. However, the findings in the present study showed decreased mass-normalized W_{ext} and higher levels of recovery in obese than in lean subjects, suggesting that obese individuals may have a better pendular mechanism that decreases the amount of work performed by the muscles to lift and accelerate the COMb relative to the surroundings. This postulation is in agreement with the results of a previous study that showed lower mass-normalized W_{ext} at higher speeds along with a higher recovery in adults with class I obesity than in lean individuals (14), and in line with an earlier finding of a reduction in relative W_{ext} by pendular exchange in African women during loaded level ground walking (19). It is hypothesized that this improved recovery in obese individuals may be attained by applying a toe-off impulse immediately before heel strike, reducing the amount of dissipative collision loss and therefore decreasing the W_{ext} needed to redirect the COMb (45). However, these results regarding a lower mass-normalized W_{ext} are in contrast with those presented by Browning et al. (4); they reported similar values in W_{ext} and recovery between obese and lean individuals. These differences between the studies may be attributed to some methodological differences; Browning et al. acquired the GRFs from a single limb, assuming gait symmetry and not considering the forces during the double support phase, thus leading to an underestimation of the W_{ext}.

Interestingly, the amount of mass-normalized W_{int} was similar between the obese adults and adults with a normal body weight, suggesting that body mass-relative W_{int} is not affected by obesity. The values presented in the lean group of individuals are in line with those predicted by Minetti et al. (30) and are similar to the results reported in previous studies in healthy young subjects (29). While the W_{int} in lean individuals has been widely investigated in the literature (2, 21), the present study is, to the best of the authors' knowledge, the first study that has quantified W_{int} in obese individuals at different walking speeds. Some authors have reported that mass-normalized W_{int} is independent of loading (16), whereas other studies found an increased amount of relative W_{int} during load carriage with military equipment (17). It is likely that these discrepancies are related to the use of different anthropometric tables to obtain the COMs and inertial properties of the segments, attesting the importance of considering interindividual differences in anthropometric properties, especially in subjects with obesity (13). Although the mass-normalized W_{int} values found in the present study were similar between the two groups, some differences arose when W_{int} was decomposed into the internal work performed by each body segment ($W_{int,LL}$, $W_{int,UL}$, and $W_{int,HT}$; Fig. 2*F* and Fig. 4*B*). These differences were statistically significant when these variables were expressed as percentages of W_{int}. As expected, $W_{int,UL}$ and $W_{int,HT}$ were higher in obese than in lean individuals, suggesting that when obese individuals are forced to walk at the same speed as their lean counterparts, they use larger upper limb movements, a strategy previously found in elderly subjects (29). Moreover, some studies have reported that enlarging the amplitude of the arm swing in between certain limits leads to a decrease in the energy cost of walking (40). This finding corroborates the present results that show an inverse correlation at the slowest speed, where stability is compromised, between the relative $W_{int,UL}$ and $W_{int,HT}$ with relative NC_w. Therefore, it seems that obese adults may use this strategy to limit the increase in mass-normalized NC_w. It has also been suggested that this increase in the arm swing amplitude has an important function



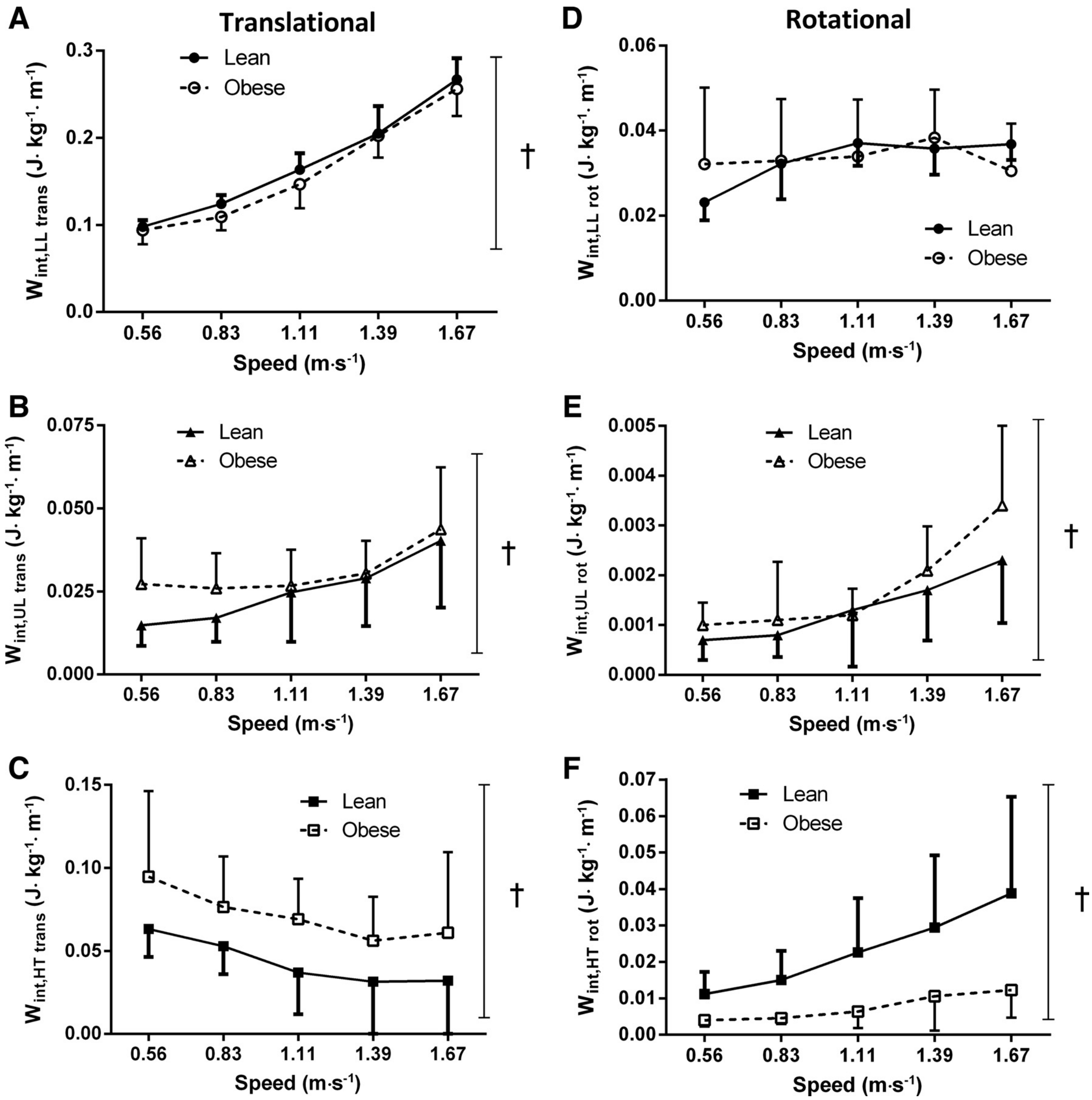


Fig. 3. Relative internal translational mechanical work of the lower limbs [$W_{int,LL\ trans}$ ($J \cdot kg^{-1} \cdot m^{-1}$)] (*A*), upper limbs [$W_{int,UL\ trans}$ ($J \cdot kg^{-1} \cdot m^{-1}$)] (*B*), and head and trunk segment [$W_{int,HT\ trans}$ ($J \cdot kg^{-1} \cdot m^{-1}$)] (*C*). Relative internal rotational mechanical work of the lower limbs [$W_{int,LL\ rot}$ ($J \cdot kg^{-1} \cdot m^{-1}$)] (*D*), upper limbs [$W_{int,UL\ rot}$ ($J \cdot kg^{-1} \cdot m^{-1}$)] (*E*), and head and trunk segment [$W_{int,HT\ rot}$ ($J \cdot kg^{-1} \cdot m^{-1}$)] (*F*). The dashed lines with open symbols correspond to the obese group (O; $n = 11$ except for 6 km/h·$n = 6$ because 5 participants were not able to complete this walking condition) and the solid lines with solid symbols correspond to the lean group (L; $n = 13$). The values are presented as means ± SD. †Significant difference ($P < 0.05$) between groups.

as a dynamic stability regulator; thus, obese individuals may also increase the amplitude of their upper limb movement to improve the balance control of their lower limbs (28, 44). In fact, as was previously found in Himalayan porters, improved postural control leads to a reduction in the internal rotational work of the head-trunk segment by minimizing the action of the antagonist muscles and preventing useless co-contractions (31), as attested by the present results (see Fig. 3). These increases in $W_{int,UL}$ and $W_{int,HT}$ in obese compared with lean subjects were not sufficiently large to affect the mass-normal-

Fig. 2. Absolute positive external mechanical work [W_{ext} (J/m)] (*A*), relative positive external mechanical work [W_{ext} ($J \cdot kg^{-1} \cdot m^{-1}$)] (*B*), absolute internal mechanical work [W_{int} (J/m)] (*C*), relative internal mechanical work [W_{int} ($J \cdot kg^{-1} \cdot m^{-1}$)] (*D*), absolute internal mechanical work of each body segment [HT: head and trunk; UL: upper limbs; LL: lower limbs; Segment W_{int} (J/m)] (*E*), relative internal mechanical work of each body segment [i.e., normalized by the total body mass; Segment $W_{int,BM}$ ($J \cdot kg^{-1} \cdot m^{-1}$)] (*F*), absolute total mechanical work [W_{tot} (J/m)] (*G*), and relative total mechanical work [W_{tot} ($J\ kg^{-1} \cdot m^{-1}$)] (*H*). The dashed lines with open symbols correspond to the obese group (O; $n = 11$ except for 6 km/h·with $n = 6$ because 5 participants were not able to complete this walking condition) and the solid lines with filled symbols correspond to the lean group (L; $n = 13$). The values are presented as means ± SD. †Significant difference ($P < 0.05$) between groups. #Significant speed × group interaction effect ($P < 0.05$). ##Trend toward a speed × group interaction effect ($P < 0.1$). [a]Significant difference ($P < 0.05$) between groups in $W_{int,LL}$. [aa]Tendency ($P < 0.1$) between groups in $W_{int,LL}$. [b]Significant difference ($P < 0.05$) between groups in $W_{int,UL}$. [c]Significant difference ($P < 0.05$) between groups in $W_{int,HT}$. *Significant difference ($P < 0.05$) between the obese and the lean group for each speed. **Tendency ($P < 0.1$) between the obese and the lean group for each speed.

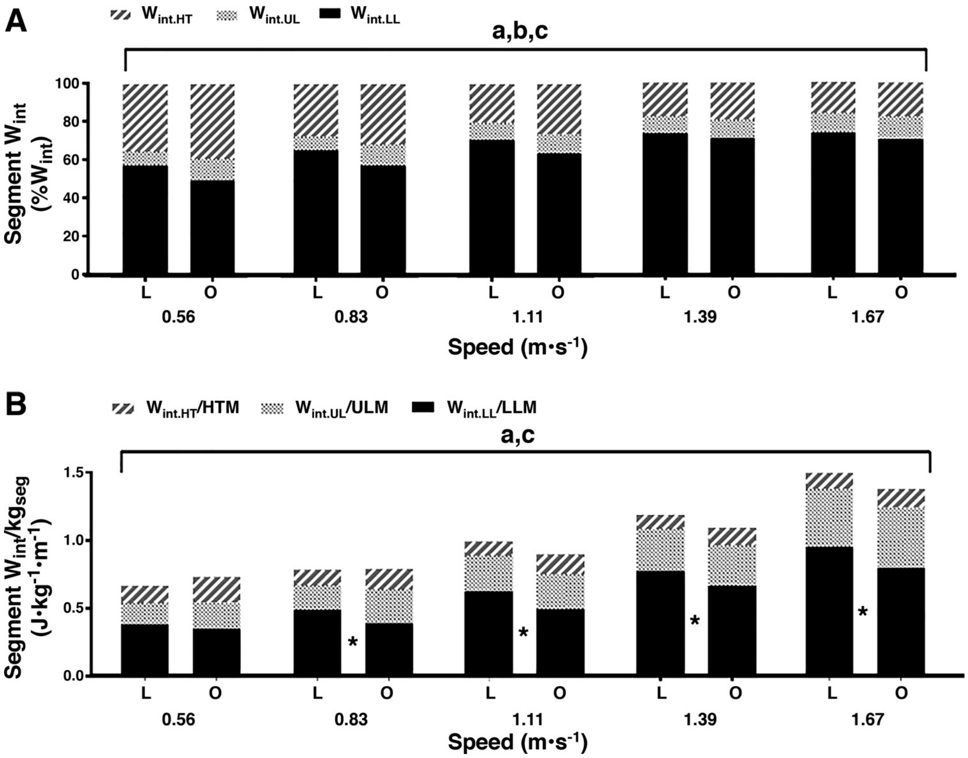


Fig. 4. Percentage of relative internal work performed by each limb [Segment W_{int} ($\%W_{int}$)] (*A*) and relative internal mechanical work of each body segment normalized by the segment mass [Segment W_{int}/kg_{seg} ($J \cdot kg^{-1} \cdot m^{-1}$)] (*B*). HTM, head and trunk mass; ULM, upper limb mass; LLM, lower limb mass. The solid black bars correspond to $W_{int,LL}$, the stippled bars correspond to $W_{int,UL}$, and the hatched bars correspond to $W_{int,HT}$. The values are presented as means. [a]Significant difference ($P < 0.05$) between groups in $W_{int,LL}$. [b]Significant difference ($P < 0.05$) between groups in $W_{int,UL}$. [c]Significant difference ($P < 0.05$) between groups in $W_{int,HT}$. *Significant difference ($P < 0.05$) between the obese and the lean group for each speed. For the sake of clarity, the SDs are not reported in this figure.

ized W_{int}, as they were compensated by a lower mass-normalized $W_{int,LL}$ compared with that of the lean group. The results of the spatiotemporal parameters found in the present study, including a shorter step length, a shorter step duration, and a longer single support duration in obese than in lean subjects, should have led to a higher $W_{int,LL}$ (30, 32). Nonetheless, a higher step frequency is associated with a shorter step length, which can lead to a similar linear and angular velocity; thus, the translational and rotational $W_{int,LL}$ may not increase. In addition, the results from the present study show that the translational component accounts for the vast majority of the W_{int} of each segment (see Fig. 3). To best of the authors' knowledge, the normalization process should also be performed by dividing the W_{int} of each limb by its respective mass rather than by the whole body mass to properly quantify the influence of the mass on the internal work performed by each limb. The weight of the lower limbs was 106% larger in the obese group than in the lean group, while the head and trunk segment was 61% heavier in the former than in the latter. These differences did not change the present results of the $W_{int,LL}$ and $W_{int,HT}$, as the $W_{int,HT}$/HTM was higher and the $W_{int,LL}$/LLM was lower in obese than in the lean group. This result suggests that obese adults may alter their walking by decreasing $W_{int,LL}$/LLM to obtain a more erect gait pattern and preserve knee muscle function (11, 15). On the other hand, no difference was found in $W_{int,UL}$/ULM between the two groups. This discrepancy with the higher $W_{int,UL}$ found in obese may indicate that, contrary to the lower limbs, the larger difference in the upper limbs mass (+98% in obese) compared with the body mass (+82% in obese) was compensated by a larger arm swing in this population. Therefore, it seems that obese adults are able to modify their gait pattern without increasing their mass-normalized W_{int}.

In addition, and regardless of the lower relative W_{ext} in these individuals, the mass-normalized W_{tot} was also similar to lean subjects. However, the external and internal contributions toward the W_{tot} were different, with a higher proportion of W_{tot} accounting for the W_{int} in the group of obese adults, suggesting that, as mentioned above, these individuals are able to reduce the impact of W_{ext} by optimizing the pendular recovery, thus

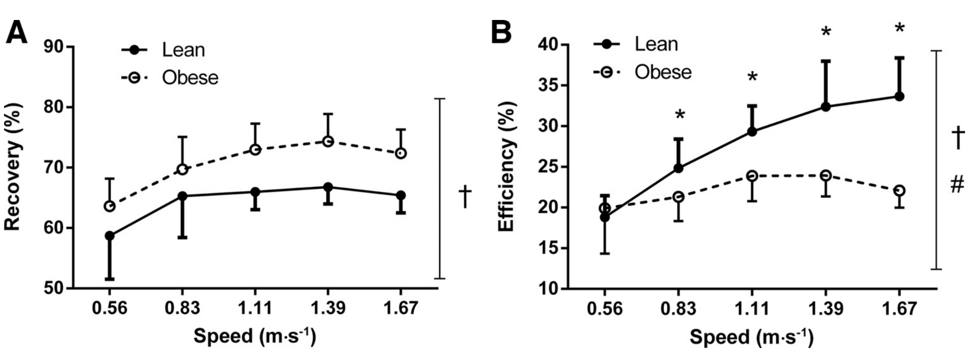


Fig. 5. Mechanical energy recovered [Recovery (%)] (*A*) and mechanical efficiency [Efficiency (%)] (*B*). The dashed lines with open circles correspond to the obese group (O; $n = 11$ except for 6 km/h·with $n = 6$ because 5 participants were not able to complete this walking condition) and the solid lines with black circles correspond to the lean group (L; $n = 13$). The values are presented as means ± SD. †Significant difference ($P < 0.05$) between groups. #Significant speed × group interaction effect ($P < 0.05$). *Significant difference ($P < 0.05$) between the obese and the lean group for each speed.

limiting the increase in W_{tot}. The similar mass-normalized W_{tot} along with a higher relative NC_w in obese subjects led to a lower efficiency in this population. As previously shown in level ground walking (26), the lower walking efficiency may be explained by the more erect gait pattern adopted by individuals with obesity (11, 15), as this gait pattern requires larger muscle activations and makes the muscles work in unfavorable conditions (e.g., increased volume of active muscle operating at disadvantageous lengths and/or velocities), wasting energy and increasing NC_w without increasing W_{tot}. This explanation corroborates previous findings of an impaired efficiency of cycling and walking in this population (22). Further studies are needed to investigate this lower mechanical efficiency of walking in obese than in lean individuals, assessing the relative contribution of the propulsive efficiency, related to the transformation of the positive work performed by the muscles into the mechanical work (i.e., the distance covered during the motion multiplied by the external friction drag), and the muscle contraction efficiency, the two components of the overall efficiency of locomotion (5).

Several limitations need to be addressed. First, the two groups were not matched for sex, age, and height. Although statistically significant, these differences were small and negligible. All our participants remained in an age range lower than the critical age (~65 yr) for changes in energetics and mechanics of walking (20, 24) and there was only a tendency in lower limb length difference between the two groups. Moreover, the findings of the present study corroborate the energetics and external mechanical work results of a previous study comparing two carefully matched groups for age and height of obese and lean individuals walking at different speeds on a treadmill (14). Second, the use of the traditional combined limb method may underestimate W_{ext}. As previously suggested, through this methodology, a considerable amount of positive and negative work that is performed simultaneously during double support phase is not accounted for (12). Third, an evaluation of the recovery within the step (8) may provide a better insight into the energy transduction between the E_k and E_p during the different phases of the gait cycle in individuals with obesity, and further studies should specifically investigate this topic. Fourth, the assessment of segment kinematics from the movement of reflective markers attached to the skin may lead to errors in measurements due to soft tissue artifacts that may affect the calculation of W_{int}, especially in obese individuals (23). In addition, and as previously stated, this W_{int} calculation may be also affected by the use of the anthropometrical tables for estimating the inertial parameters of the body segments in our group of lean adults. However, the latter values are in line with those previously reported in this population (29, 30). Moreover, some authors have reported that parts of the leg swing and arm swing movements are passive, requiring no muscular action and leading to an overestimation of the effect of the W_{int} on NC_w (36). Fifth, the results regarding the mass-normalized W_{tot} should be interpreted carefully due to the low statistical power in this analysis, suggesting that more studies are needed to confirm our results. Besides, the estimation of W_{tot} as the sum of W_{ext} and W_{int} has been discussed. Some studies have reported that these two components of W_{tot} are not necessarily independent and that some energy transfer between the two components may take place (2, 21). Finally, and taking into account that the body composition was assessed via iDXA only for the obese participants, future studies are needed to measure the body composition also in normal body weight individuals, to better compare the energetics and mechanics of walking in both groups of population. In addition, this may provide a better insight regarding how the mass-normalization of the variables (i.e., kg of total body mass vs. kg of lean mass vs. kg of muscle mass) should be performed.

In summary, individuals with class III obesity and individuals with a normal body weight exhibit similar amounts of mass-normalized internal mechanical work. Obese adults may adapt their gait pattern to compensate for the different amounts of internal work performed at each segment level, thereby limiting the increase in global relative internal mechanical work. Moreover, regardless of the lower amount of mass-normalized external mechanical work and the higher recovery arising from these gait adaptations, the total amount of relative mechanical work remains similar to that of lean individuals. As a consequence, the mechanical efficiency is reduced in obese individuals due to their higher energy cost of walking. These findings suggest that mass-normalized internal work as well as total mechanical work are not affected by obesity and are not responsible for the higher relative energy cost and lower efficiency in this population. The strategies adopted by obese individuals to lower the internal work of moving lower limbs, and to improve the pendular recovery for reducing external work, may minimize the increase in the energy cost of walking that is likely related to muscle level differences (e.g., more muscle fiber work or force and/or poorer muscle efficiency compared with lean individuals).

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DISCLAIMERS

The results of the present study do not constitute endorsement by the ACSM.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

A.F.M., L.F., D.H., and D.M. conceived and designed research; A.F.M. and D.M. performed experiments; A.F.M., B.U., F.B., and D.M. analyzed data; A.F.M. and D.M. interpreted results of experiments; A.F.M. prepared figures; A.F.M. drafted manuscript; A.F.M., B.U., L.F., D.H., F.B., and D.M. edited and revised manuscript; A.F.M., B.U., L.F., D.H., F.B., and D.M. approved final version of manuscript.

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