Obesity does not increase external mechanical work per kilogram body mass during walking

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ABSTRACT

Walking is the most common type of physical activity prescribed for the treatment of obesity. The net metabolic rate during level walking (W/kg) is $\sim$10% greater in obese vs. normal weight adults. External mechanical work (W_{ext}) is one of the primary determinants of the metabolic cost of walking, but the effects of obesity on W_{ext} have not been clearly established. The purpose of this study was to compare W_{ext} between obese and normal weight adults across a range of walking speeds. We hypothesized that W_{ext} (J/step) would be greater in obese adults but W_{ext} normalized to body mass would be similar in obese and normal weight adults. We collected right leg three-dimensional ground reaction forces (GRF) while twenty adults (10 obese, BMI = 35.6 kg/m^2 and 10 normal weight, BMI = 22.1 kg/m^2) walked on a level, dual-belt force measuring treadmill at six speeds (0.50–1.75 m/s). We used the individual limb method (ILM) to calculate external work done on the center of mass. Absolute W_{ext} (J/step) was greater in obese vs. normal weight adults at each walking speed, but relative W_{ext} (J/step/kg) was similar between the groups. Step frequencies were not different. These results suggest that W_{ext} is not responsible for the greater metabolic cost of walking (W/kg) in moderately obese adults.

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1. Introduction

The prevalence of obesity continues to increase (Ogden et al., 2006) and is due, in part, to inadequate physical activity (Metzger et al., 2008). Walking is recommended for the prevention and treatment of obesity because it is a convenient type of physical activity that can be used to expend a significant amount of metabolic energy. Obese adults have a net metabolic rate during level walking (C_w, W/kg) that is $\sim$10% greater than normal weight adults (Browning et al., 2006; Mattsson et al., 1997). The biomechanical explanation for this greater metabolic rate is not known. It may be that obesity elicits changes in gait biomechanics (e.g. wide walking stance) that requires greater external mechanical work to be performed. It is also possible, however, that other biomechanical determinants are responsible for the greater C_w in obese individuals.

There are several biomechanical determinants of C_w. These include external mechanical work (W_{ext}), body weight support, leg swing, step width and lateral leg swing circumduction. In normal weight adults, W_{ext} accounts for $\sim$50% of C_w (Grabowski et al., 2005). The traditional, combined limbs method (CLM) of measur-

ing W_{ext} approximates the body as a point mass located at the center of mass and the action of the legs as a single, combined force applied to the point mass. Instantaneous mechanical power is calculated as the dot product of the ground reaction force (GRFs) and the center of mass velocities and the time integral of mechanical power yields W_{ext} (Cavagna, 1975; Cavagna et al., 1977). The CLM has been used to show that an inverted-pendulum mechanism conserves mechanical energy during walking. By combining the GRF's of the leading and trailing legs, the CLM method ignores the simultaneous positive and negative work done by the trailing and leading legs during double support and thus underestimates W_{ext} (Donelan et al., 2002a). An alternative approach is to measure W_{ext} performed by the individual legs. The individual limbs method (ILM), accounts for the work required to transition from one inverted pendulum to the next during double support (i.e. the step-to-step transition). The forces generated by each leg are used to calculate instantaneous power, which are then integrated to quantify W_{ext}. Using this individual limbs method (ILM), Donelan et al. reported that W_{ext} during walking was $\sim$33% greater compared to W_{ext} calculated using the CLM (Donelan et al., 2002a). Further, another study by Donelan et al. suggested that the W_{ext} required to redirect the center of mass during the step-to-step transition is a major determinant of C_w, because C_w increased directly with W_{ext} required to redirect the center of mass (Donelan et al., 2002b).

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To date, only two studies have described the effects of obesity on W_{ext}. Malatesta et al. (Malatesta et al., 2009) reported that W_{ext} (J/kg/m) using the CLM was similar in obese vs. normal weight adults. However, their obese subjects were walking at a self-selected speed that was slower than the speed selected by normal weight subjects and W_{ext} is affected by walking speed (Willems et al., 1995). Peyrot et al. (2009) had obese and normal weight adolescents walk at matched speeds and found no differences in W_{ext} (J/kg/m) using the CLM. Recent studies that have quantified the biomechanics of walking at a set speed in moderately obese vs. normal weight adults report no differences in stride length/frequency or body weight normalized GRFs (Browning and Kram, 2007; Messier et al., 1996). As these variables affect the primary determinants of W_{ext}, this further supports the idea that W_{ext} (J/step/kg) may not be altered by moderate obesity. However, obese adults walk with wider steps (Browning and Kram, 2007; Spyropoulos et al., 1991), and step width has been shown to increase the W_{ext} required during step-to-step transitions (Donelan et al., 2001), albeit to a lesser degree than step length (Donelan et al., 2002a).

We hypothesized that at identical walking speeds, W_{ext} (J/step) would be greater in obese adults but W_{ext} normalized to body mass (J/step/kg) would be similar in obese and normal weight adults. Therefore, the purpose of this study was to compare absolute and normalized W_{ext} (ILM) between obese and normal weight adults across several walking speeds.

2. Methods

2.1. Subjects

Two groups of young adults volunteered for this study: obese ($n = 10$, 5 females and 5 males) and normal weight ($n = 10$, 5 females and 5 males). BMI was used to classify the participants; obese subjects had BMI values of 30–40 kg/m^2 and normal weight subjects had BMI values of 18–25 kg/m^2. All subjects were in good health and body mass stable (<2.5 kg net change over the previous three months). Subjects gave written informed consent that followed the guidelines of the University of Colorado Human Research Committee. The physical characteristics of the groups are shown in Table 1.

2.2. Experimental protocol

Each subject performed six level walking trials on a dual-belt force measuring treadmill. First, we familiarized the subjects to the treadmill by having them walk for at least 10 min at a comfortable walking speed. The familiarization was followed by the experimental trials. The treadmill speeds were 0.50, 0.75, 1.00, 1.25, 1.50, and 1.75 m/s and the trial order was randomized for each subject. During each trial, subjects walked with the right leg on the right treadmill and the left leg on the left treadmill for 2 min, followed by two minutes of walking with both feet on the right treadmill.

2.3. Ground reaction forces

We measured ground reaction forces using a dual-belt force measuring treadmill. The treadmill is a hybrid of the designs developed by Kram et al. (1998) and Belli et al. (2001) with the force plate under the right treadmill (Browning and

Table 1
Physical characteristics of obese and normal weight females and males.

Physical characteristic	Female		Male	
	Obese ($n = 5$)	Normal ($n = 5$)	Obese ($n = 5$)	Normal ($n = 5$)
BMI (kg/m^2)	37.0 (6.0)	21.0 (0.8)	34.1 (3.7)	23.1 (1.6)
Body Mass (kg)	106.2 (25.1)	58.5 (2.1)	115.0 (16.4)	76.8 (4.5)
Height (m)	1.69 (0.08)	1.67 (0.04)	1.83 (0.07)	1.82 (0.03)
Age (years)	31.0 (7.1)	31.8 (5.7)	26.8 (7.6)	25.6 (9.8)

Values are mean (SD).

Kram, 2007). The right and left treadmill belts were separated by less than 1 cm. We collected right leg vertical, anterior–posterior (AP) and medio-lateral (ML) ground reaction forces and moments about the AP and ML axis for 10 s at 1000 Hz. GRF data were collected during the last 30 s of each trial. The ground reaction force data were filtered using a recursive fourth-order Butterworth low-pass filter with a cutoff frequency of 12 Hz. We used the GRF data to determine right heel strike and toe-off. GRF and stride characteristic data for these subjects have been reported in a previous publication (Browning and Kram, 2007).

2.3.1. Step width

Step width was determined by calculating the distance between mid-stance medio-lateral center of pressure location of successive steps while subjects walked with both feet on the right treadmill (Donelan et al., 2004).

2.4. External mechanical work

We used the individual limb method (ILM) (Donelan et al., 2002a) to calculate W_{ext} done on the center of mass during five consecutive strides. The average right leg force data for a stride were phase-shifted by 50%, assuming symmetry (Seeley et al., 2008), and the ML forces were multiplied by -1 to reverse the polarity to emulate forces produced by the left leg. The timing of double and single support within a step cycle was determined from the phase-shifted vertical GRF data. Center of mass (CoM) velocity was determined by integrating (with respect to time) the combined forces from both legs acting on the center of mass (Cavagna, 1975).

$$v_{z,com} = \int \frac{F_{z,trail} + F_{z,lead} - mg}{m} \, dt, \tag{1}$$

$$v_{y,com} = \int \frac{F_{y,trail} + F_{y,lead}}{m} \, dt, \tag{2}$$

$$v_{x,com} = \int \frac{F_{x,trail} + F_{x,lead}}{m} \, dt. \tag{3}$$

In Eqs. (1)–(3), F_{trail} and F_{lead} are the GRFs acting on the double support trailing and leading legs, respectively. v_{com} is the velocity of the center of mass and the subscripts z, y and x denote the vertical, anterior–posterior and medio-lateral directions, respectively.

Individual limb power was calculated as the dot product of the CoM velocity and right leg GRF (see Fig. 1 for intermediate results showing these quantities) and ILM work was calculated by integrating the power curve with respect to time.

$$P_{trail} = \vec{F}_{trail} \cdot \vec{v}_{com} = F_{z,trail}v_{z,com} + F_{y,trail}v_{y,com} + F_{x,trail}v_{x,com}, \tag{4}$$

$$P_{lead} = \vec{F}_{lead} \cdot \vec{v}_{com} = F_{z,lead}v_{z,com} + F_{y,lead}v_{y,com} + F_{x,lead}v_{x,com}, \tag{5}$$

$$W_{ILM}^{+} = \int_{POS} P_{trail} \, dt + \int_{POS} P_{lead} \, dt, \tag{6}$$

$$W_{ILM}^{-} = \int_{NEG} P_{trail} \, dt + \int_{NEG} P_{lead} \, dt. \tag{7}$$

In Eqs. (4)–(7), P_{trail} and P_{lead} are the external mechanical powers generated by the trailing and leading limbs, respectively. W_{ILM}^{+} and W_{ILM}^{-} is the sum of the positive (POS) or negative (NEG) external mechanical work performed by each leg during contact with the ground.

We also used the combined GRFs (resultant, F_{res}) to calculate the kinetic and potential energies of the CoM, CLM W_{ext} and the inverted-pendulum recovery of mechanical energy (Cavagna, 1975; Griffin et al., 1999; Schepens et al., 2004).

$$P_{CLM} = \vec{F}_{res} \cdot \vec{v}_{com} = F_{z,res}v_{z,com} + F_{y,res}v_{y,com} + F_{x,res}v_{x,com}, \tag{8}$$

$$W_{CLM}^{+} = \int_{POS} P_{CLM} \, dt, \tag{9}$$

$$W_{CLM}^{-} = \int_{NEG} P_{CLM} \, dt, \tag{10}$$

$$Recovery = 100 \times \frac{W_k + W_p - W_{CLM}^{+}}{W_k + W_p}. \tag{11}$$

In Eqs. (8)–(11), P_{CLM} is the external mechanical power generated by both legs. W_{CLM}^{+} and W_{CLM}^{-} is the sum of the positive (POS) or negative (NEG) external mechanical work. W_k and W_p are the sum of the positive increments in the kinetic and potential energy of the CoM.
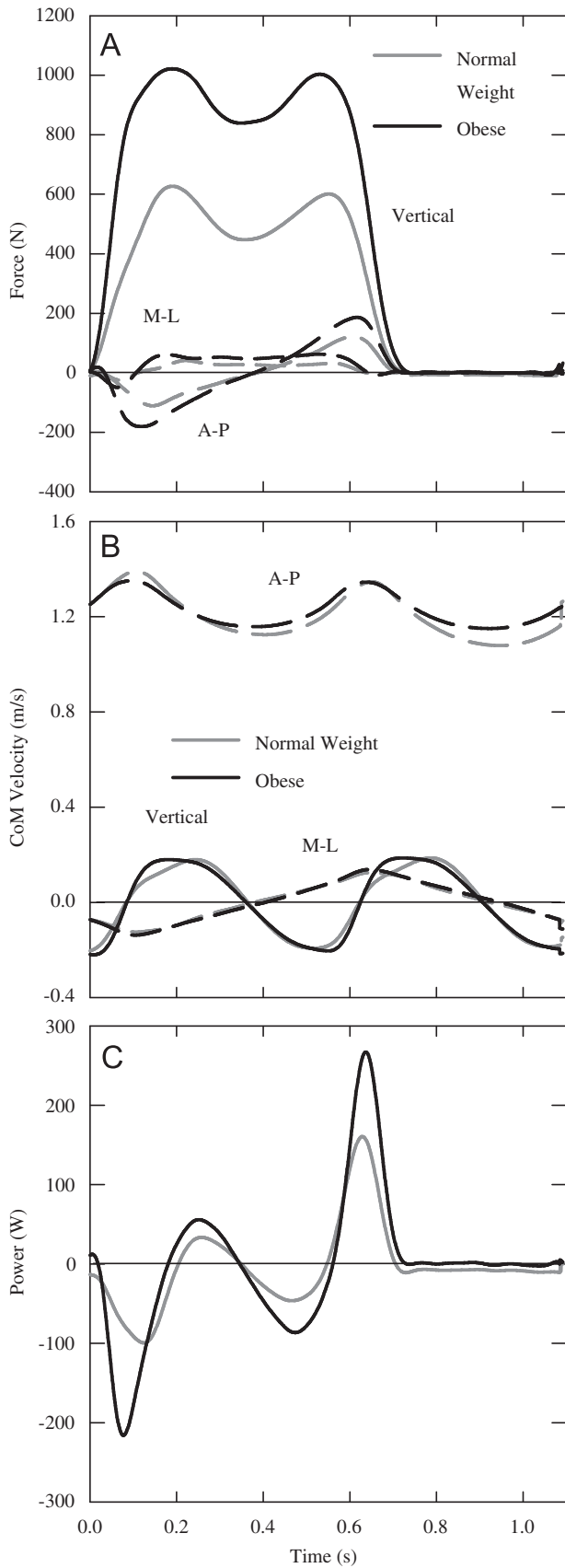
Fig. 1. Ground reaction forces (A), center of mass velocities computed from ground reaction forces (B) and total power computed from the dot product of the GRF and center of mass velocities (C) during a typical single step for normal weight (body mass = 59 kg, BMI = 22.2 kg/m²) and obese (body mass = 105 kg, BMI = 35.5 kg/m²) subjects walking at 1.25 m/s. Obese adults had greater absolute GRFs but center of mass velocities were similar. As a result, absolute external mechanical power (W) was greater for obese vs. normal weight individuals.
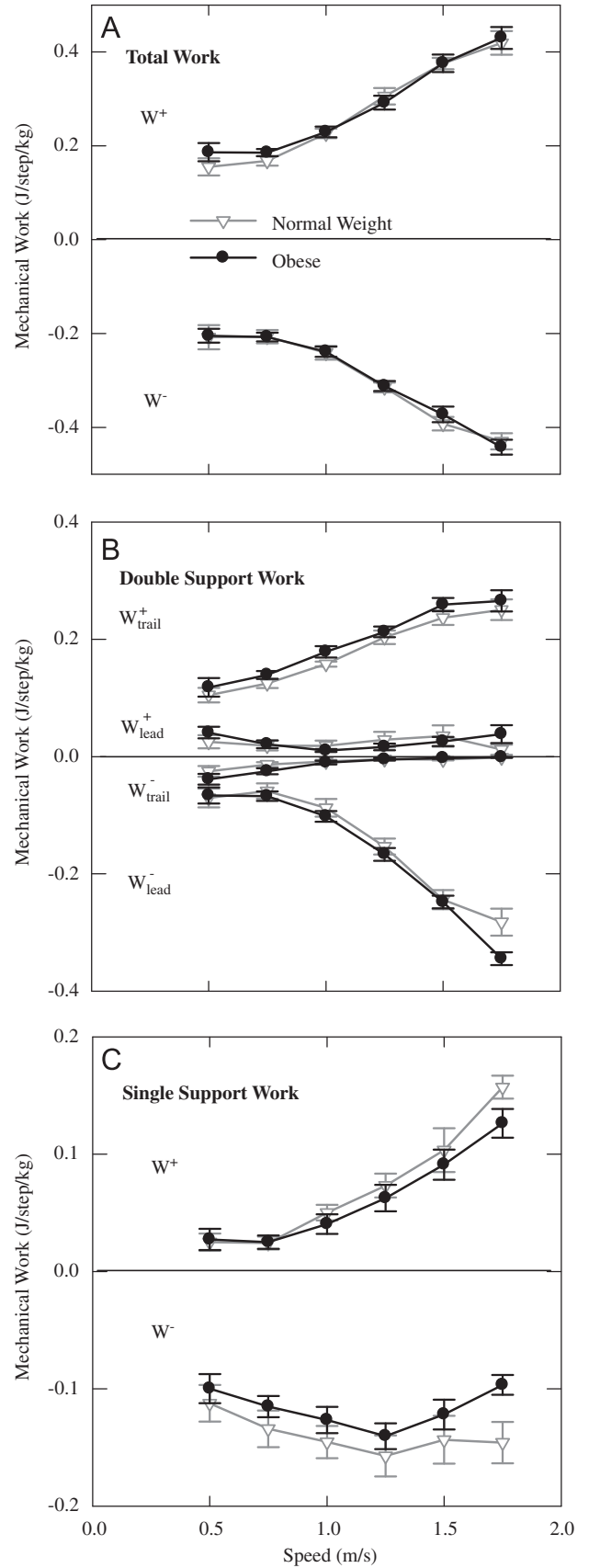
Fig. 2. External positive (W^+) and negative (W^-) mechanical work (J/step/kg) for normal weight and obese subjects during a step (A), double support (B), and single support (C). All data are mean (SE). There were no significant differences in external work between the groups during a step, double support or single support. During double support, the trailing leg performed primarily positive work while the leading leg performed primarily negative work.

Table 2
Mean (SE) total, vertical (V), horizontal (H) and lateral (L) positive external work (J/step/kg) for each group and walking speed.

Speed (m/s)	Total[+]		V[+]		H^{+}		L[+]	
	O	N	O	N	O	N	O	N
0.50	0.186 (0.019)	0.155 (0.018)	0.212 (0.026)	0.149 (0.024)	0.138 (0.006)	0.106 (0.008)	0.014 (0.005)	0.008 (0.002)
0.75	0.185 (0.008)	0.168 (0.010)	0.247 (0.013)	0.207 (0.013)	0.211 (0.014)	0.184 (0.009)	0.015 (0.002)	0.011 (0.002)
1.00	0.229 (0.011)	0.226 (0.010)	0.293 (0.018)	0.272 (0.022)	0.303 (0.016)	0.275 (0.016)	0.016 (0.003)	0.010 (0.002)
1.25	0.292 (0.015)	0.305 (0.017)	0.358 (0.019)	0.339 (0.019)	0.402 (0.013)	0.385 (0.018)	0.014 (0.002)	0.008 (0.001)
1.50	0.376 (0.019)	0.375 (0.012)	0.425 (0.025)	0.415 (0.019)	0.528 (0.018)	0.508 (0.016)	0.012 (0.002)	0.007 (0.001)
1.75	0.430 (0.023)	0.419 (0.025)	0.456 (0.028)	0.449 (0.027)	0.603 (0.029)	0.586 (0.033)	0.010 (0.002)	0.007 (0.001)

O = obese, N = normal weight.

The vertical and horizontal integration constants were determined such that the average vertical velocity over a step was zero and the average horizontal velocity was equal to the treadmill belt speed, respectively. The medio-lateral integration constant was determined such that the medio-lateral velocities and the beginning and end of a step were equal in magnitude but opposite in sign.

2.5. Statistical analysis

A two-factor (obesity and speed) ANOVA with repeated measures determined how walking obesity and speed affected W_{ext}. If a significant main effect was observed, post-hoc comparisons using the Newman–Keuls method were performed. A criterion of $p < 0.05$ defined significance. Unless otherwise noted, only the results of group main effects are reported.

3. Results

3.1. Gait characteristics

Stride length and stride frequency were not different between the groups at any walking speed ($p = 0.50$, $p = 0.57$, respectively) (Browning and Kram, 2007). Compared to normal weight adults, obese adults spent more time in stance at the slower walking speeds (0.50–1.25 m/s) and had a longer period of double support at all walking speeds. The obese adults had greater absolute GRFs (N) (Fig. 1), but body mass specific GRFs (N/kg) were similar between the obese and normal weight groups. Step width was ~30% greater in the obese vs. normal weight participants (0.150 (0.015) vs. 0.115 (0.012) m, mean (S.D.), $p = 0.008$) and did not change significantly with walking speed ($p = 0.48$).

3.2. ILM external mechanical work

Absolute total positive and negative W_{ext} (W_{ext}^+, W_{ext}^-, respectively, J/step) was significantly greater in obese vs. normal weight adults at each walking speed ($p < 0.001$). When normalized to body mass, total W_{ext}^+ and W_{ext}^- (J/step/kg) was similar between the groups ($p = 0.88$ and $p = 0.64$) (Fig. 2A). Total W_{ext}^+ and W_{ext}^- (J/step/kg) increased ~2 fold as speed increased from 0.5 to 1.75 m/s. Vertical and horizontal (anterior–posterior) work were the primary determinants of total W_{ext}^+ and W_{ext}^-. Lateral work was small (<3% of total work) for both groups (Table 2).

During double support, external work (J/step/kg) performed by the trailing (W_{trail}^+, W_{trail}^-) and leading legs (W_{lead}^+, W_{lead}^-) was similar between the groups (Fig. 2B). The trailing leg performed ~80–95% of the positive work and the leading leg performed ~75–99% of the negative work during double support, with the greatest percentages at the faster walking speeds. Both W_{trail}^+ and W_{lead}^- increased with walking speed. Horizontal (anterior–posterior) work was the primary determinant of W_{trail}^+ and W_{lead}^-. During single support, W^+ and W^- were similar between groups
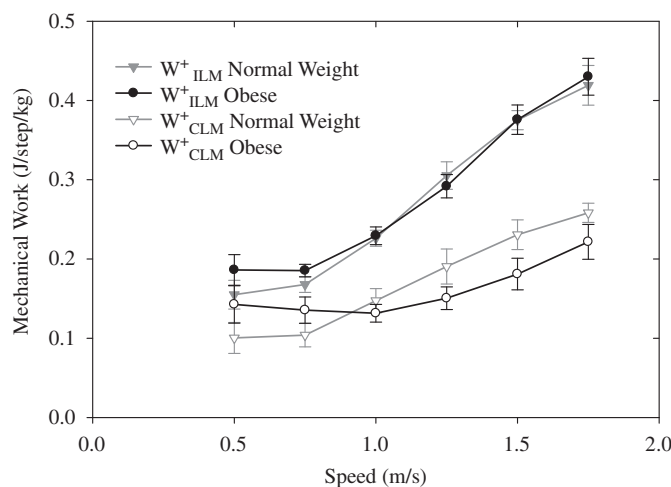

Fig. 3. Individual limbs method (ILM) vs. combined limbs method (CLM) measures of total positive external work (J/step/kg) across the range of speeds in obese and normal weight individuals. Data are mean (SE). CLM significantly underestimated positive W_{ext}.

(Fig. 2C). Single support W^+ increased with walking speed while single support W^- increased as walking speed increased from 0.5 to 1.25 m/s and then decreased slightly at the faster speeds.

3.3. CLM external mechanical work

External work as determined using the combined limbs method was less than when using the ILM method. The differences between the methods ranged from ~25% to 50%, depending on walking speed (Fig. 3). There were no differences in CLM external work (J/step/kg) between the groups ($p = 0.43$). CLM external work increased with walking speed. Recovery of mechanical energy was similar between the groups (mean across all speeds of 69% vs. 66% for obese and normal weight, respectively, $p = 0.37$).

4. Discussion

We accept our hypothesis that normalized W_{ext} (J/step/kg) would be similar for obese and normal weight adults during level walking over a range of speeds. The ILM W_{ext} values reported here for a step, double support and single support are similar to values reported for normal weight individuals (Donelan et al., 2002a). Donelan et al. reported positive W_{ext} of ~0.3 J/step/kg during overground walking at 1.25 m/s, while we measured W_{ext} of

0.29 J/step/kg in the obese and 0.31 J/step/kg in the normal weight participants for treadmill walking at the same speed.

When walking at the same speed, our results suggest that moderately obese adults do not adjust their gait to reduce the external mechanical work done on the CoM. Thus, the greater net metabolic rate during walking is not likely due to moderately obese individuals having to perform more external mechanical work (per kg body mass) compared to their normal weight counterparts. This finding was not unexpected given the similarities in stride characteristics (e.g. stride length) and relative GRFs between the groups. Although the moderately obese participants had greater medio-lateral GRFs, the contribution of lateral work to W_{ext}, was small. This small contribution can be explained by the modest increase in preferred step width (~30%) adopted by the obese participants. Donelan et al. (2001) reported that normal weight adults preferred a step width of ~0.13 L (L = leg length) and when step width was increased by 50% (from 0.10 to 0.15 L) there was only a small increase (~10%) in mechanical cost. Selection of preferred step width is likely a trade-off between minimizing step-to-step transition work and the work required for lateral leg swing circumduction. The step width preferred by moderately obese adults suggests that lateral leg swing may be more mechanically costly for this group. It may also be that the wider step width adopted by the moderately obese adults is partly due to a desire to reduce the friction between the legs. Future studies that examine the relationship between obesity and the cost of leg swing would provide insights into selection of preferred step width.

The CLM significantly underestimated W_{ext} performed during walking for both the moderately obese and normal weight groups. This underestimation of W_{ext} is due to the simultaneous positive and negative work by the trailing and leading limbs that reduces the summed power generated by the limbs (Donelan et al., 2002a). Previous studies have reported that the CLM underestimates W_{ext} by ~31–33% in normal weight adults walking across a range of speeds (Donelan et al., 2002a, 2002b). We found that CLM underestimated W_{ext} by ~25–50%. Our values of W_{ext} using the CLM method are similar to those reported by others for normal weight adults (Donelan et al., 2002a; Willems and Huijing, 1994), but less than those reported for obese adults by Malatesta et al. (2009) (0.23 J/step/kg at 1.18 m/s in Malatesta et al. vs. 0.15 J/step/kg at 1.25 m/s in this study) and adolescents (Peyrot et al., 2009). The differences in CLM W_{ext} between our study and Malatesta et al. and Peyrot et al. may be attributed to methodology, as they used an optoelectronic system and accelerometers, respectively, to quantify CoM motion, rather than force plates. Although motion analysis techniques using passive markers or accelerometers may be suitable for quantifying CoM motion in normal weight subjects, there is the possibility that excessive marker or device movement in obese subjects may result in errors in calculating CLM W_{ext}. Another potential factor that may account for some of the difference in CLM W_{ext} is the degree of adiposity of the obese populations. Compared to our subjects, the subjects used in the Malatesta et al. study where heavier and more obese (mean BMI ~40 kg/m²). The data of DeVita and Hortobagyi (2003) suggest that when BMI exceeds 40 kg/m², individuals may adjust their gait and walk with a straighter leg, which could alter W_{ext}.

Given that W_{ext} is a primary determinant of the metabolic cost of walking, ILM measures of W_{ext} should provide better predictions of the metabolic cost of walking than those that use the CLM. Although the CLM does not account for all W_{ext} during a step, it is the basis for measures of recovery of mechanical energy during a step (% recovery). It has been shown that experienced head-load carriers walk with greater recovery of mechanical energy (when carrying a load), which has been proposed as the explanation for

their ability to carry up to 20% of body weight without an increase in metabolic cost (Heglund et al., 1995). Our results show that moderate obesity does not result in improved recovery or less mechanical work being performed during walking and, as a result, is not responsible for the greater metabolic cost of walking in obese adults. This also suggests that while habituated walking with a head-supported load elicits changes in gait mechanics, moderate obesity does not. Perhaps part of this adaptive response in the head-load carrying populations is due to the magnitude of daily walking, which is likely to be much greater than a sedentary, moderately obese individual. It should be noted that there are clear examples where there is not a strong link between the calculated inverted-pendulum recovery and the metabolic cost of walking (Zani et al., 2005).

Recently, it has been suggested that the efficiency of muscle mechanical work during low intensity cycle ergometry (10–25 W) increases in obese individuals who have undergone ~10% weight loss (Rosenbaum et al., 2003). Rosenbaum et al. selected these low power outputs to mimic the intensity of typical lifestyle activities of sedentary, obese individuals (e.g. slow walking) (Rosenbaum et al., 2003). Given the ability of the ILM to accurately measure W_{ext}, it seems a more direct measure of "lifestyle activity" mechanical efficiency would be to measure W_{ext} via ILM and the metabolic cost of walking simultaneously in weight-reduced obese individuals. Such a study would provide valuable insights into the magnitude of adaptive thermogenesis (Spiegelman and Flier, 2001) associated with weight loss.

The similarity in W_{ext} between the normal weight and obese groups implies that other biomechanical determinants may be responsible for the greater net metabolic rate of walking in moderately obese adults. Body weight support accounts for a significant portion (~25%) of C_w (Grabowski et al., 2005) in normal weight adults. It is possible that obesity increases the cost of supporting body weight because obese adults have reduced relative strength compared to normal weight adults (Hulens et al., 2001). This reduced strength could require an increase in muscle activation to support body weight. In normal weight adults, leg swing accounts for ~10% of C_w (Gottschall and Kram, 2005) and increasing step width by 50% increases C_w by ~13% (Donelan et al., 2001). The combination of body weight support, swinging heavier legs and walking with wider steps seems to be the most probable factors for the modestly greater C_w in moderately obese adults. Future experiments designed to assess these biomechanical determinants of the metabolic cost of walking are needed in order to gain a comprehensive understanding of the relationship between obesity and walking energy expenditure.

The use of single leg force data and treadmill walking may represent limitations to this study. The treadmill used in this study had a single force plate under the right belt, thus we used only single leg data and assumed gait symmetry. Although this assumption may be debatable (Sadeghi et al., 2000), we are not aware of data that would suggest that obese individuals walk with more or less symmetry compared to normal weight individuals. In addition, caution may be warranted when translating treadmill biomechanics data to overground walking. However, differences in gait kinematics and kinetics are small during treadmill vs. overground walking (Riley et al., 2006) and the recent finding that W_{ext} is not effected by obesity during overground walking (Malatesta et al., 2009), suggests our results can be applied to overground walking.

In summary, while moderately obese individuals perform more absolute W_{ext} (J/step), they do not perform more normalized W_{ext} (J/step/kg) than their normal weight peers when walking across a range of speeds. When walking at a specific speed, obesity may not result in alterations to gait biomechanics that serve to change W_{ext}. Our results suggest that while W_{ext} is one of the primary

determinants of the metabolic cost of walking, W_{ext} is not responsible for the greater metabolic cost of walking in moderately obese adults.

Conflict of interest statement

The authors report no conflict of interest.

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