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Characteristic Gait Patterns in Older Adults with Obesity - Results from the Baltimore Longitudinal Study of Aging

Seung-uk Ko¹, Sari Stenholm^{1,2}, and Luigi Ferrucci¹

¹ Clinical Research Branch, NIA, Baltimore, MD, USA ² National Institute for Health and Welfare, Helsinki, Finland

Abstract

Obesity in older adults is a growing public health problem. Excess weight causes biomechanical burden to lower extremity joints and contribute to joint pathology. The aim of this study was to identify specific characteristics of gait associated with body mass index (BMI). Preferred and maximum speed walking and related gait characteristics were examined in 164 (50–84 years) participants from Baltimore Longitudinal Study of Aging (BLSA) able to walk unassisted. Participants were divided into three groups based on their BMI: normal weight ($19 \leq \text{BMI} < 25 \text{ kg/m}^2$), overweight ($25 \leq \text{BMI} < 30 \text{ kg/m}^2$) and obese ($\text{BMI} 30 \leq \text{BMI} < 40 \text{ kg/m}^2$). Total ankle generative mechanical work expenditure (MWE) in the anterior-posterior (AP) plane was progressively and significantly lower with increasing BMI for both preferred ($p = 0.026$) and maximum speed walking ($p < 0.001$). In the medial-lateral (ML) plane, total knee generative MWE was higher in obese participants in the preferred speed task ($p = 0.002$), and total hip absorptive MWE was higher in obese in both preferred speed ($p < 0.001$) and maximum speed ($p = 0.002$) walking task compared to the normal weight participants. Older adults with obesity show spatiotemporal gait patterns which may help to reduce contact impacts. In addition, in obese persons mechanical energy usages tend to be lower in the AP plane and higher in the ML plane. Since forward progression forces are mainly implicated in normal walking, this pattern found in obese participants is suggestive of lower energetic efficiency.

Keywords

Gait; Obesity; Gait speed; Mechanical work expenditure; BMI

INTRODUCTION

The number of older obese adults is increasing in the United States as well as in other westernized countries (Mokdad et al., 2001; Wang and Beydoun, 2007). Obesity is a known risk factor for several diseases (WHO, 2000), and also negatively affects physical functioning,

Contact information for the corresponding author: Seung-uk Ko, Ph.D. National Institute on Aging (NIA) Clinical Research Branch, Harbor Hospital 3001 S. Hanover Street, Baltimore, MD 21225, USA Phone: 1-541-908-2727, Fax: 1-410-350-7304 kos2@mail.nih.gov.

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Conflict of interest

All the authors declare that no financial or personal relationships were conducted with other people or organizations that could inappropriately influence or bias this work.

especially walking ability and performance (Houston et al., 2009; Stenholm et al., 2007). Studies have shown that walking ability is an important prerequisite for autonomy in activities of daily living. Understanding mechanisms that may affect the ability to walk in older individuals may help identifying target for prevention and rehabilitation. Lower extremity osteoarthritis (OA) is the cause of disability that older people report most often (McAlindon et al., 1993; van Baar et al., 1998). Interestingly, obesity is one of the main risk factors for knee and hip OA (Anderson and Felson, 1988; Grazio and Balen, 2009) and recent data have shown that obesity is cross sectionally associated with low walking speed and predicts the development of mobility disability (Houston et al., 2009; Stenholm et al., 2007). However, the mechanisms that link obesity, joint pathology and walking ability remain unclear. It is possible that excess body weight causes a biomechanical burden to lower extremity joints (Ling et al., 2003), that in turn leads to degenerative joint disease and, eventually, to walking impairment.

In previous studies obesity was associated with slower gait speed (Lai et al., 2008; McGraw et al., 2000; Spyropoulos et al., 1991), wider step width (Spyropoulos et al., 1991), higher hip medial-lateral (ML) rotation (Lai et al., 2008; Spyropoulos et al., 1991) and lower ankle anterior-posterior (AP) joint moment (Lai et al., 2008). Researchers have suggested that these characteristics develop as adaptations to excess weight loading on the knee joints while walking (Gyory et al., 1976; Stauffer et al., 1977). These findings were based on relatively small number of young obese individuals. Because older age is associated with poor lower extremity performance, it is reasonable to believe that the effect of obesity on gait pattern may be even higher than previously identified in younger individuals. However, to our knowledge, there are no previous studies about gait characteristics in older adults with obesity.

Using data from 164 older adults enrolled in the Baltimore Longitudinal Study of Aging with a wide range of body mass index (BMI) we compared gait characteristics between those with normal weight, overweight, and obesity. We hypothesize that obesity is associated with altered spatiotemporal characteristics and mechanical work expenditure (MWE) in lower extremities while walking at preferred and maximum speed walking.

METHODS

Participants

Data were collected in 164 participants in the Baltimore Longitudinal Study of Aging (BLSA) who were between 50 and 84 years old. The study was conducted in the Clinical Research Branch Gait Laboratory (NIA, NIH) between January and August of 2008. Participants who did not have hip or knee joint prosthesis, severe joint pain, history of stroke or Parkinson's disease, and who were able to follow instructions and safely complete at least the preferred speed walking test unaided were included in the study. The BLSA protocol was approved by the Medstar Research Institution Review Board (Baltimore, MD). Participants were given a detailed description of the study and they consented to participate.

Body Mass Index

BMI was calculated as objectively measured weight divided by measured height squared (kg/m^2). According to World Health Organization criteria (WHO, 2000), participants were classified into three groups, namely normal weight ($19 \leq \text{BMI} < 25 \text{ kg}/\text{m}^2$; $N=56$), overweight ($25 \leq \text{BMI} < 30 \text{ kg}/\text{m}^2$; $N=74$), and obese ($30 \leq \text{BMI} < 40 \text{ kg}/\text{m}^2$; $N=34$). Participants who had BMI over $40 \text{ kg}/\text{m}^2$ were not included in this study because of the technical difficulties positioning the pelvic markers needed in gait analysis.

Gait measurements

The procedure for the gait analysis performed in our laboratory has been described elsewhere (Ko et al., 2009; Teixeira-Salmela et al., 2008). Briefly, participants were instrumented with 20 reflective markers in anatomical landmarks: anterior and posterior superior iliac spines, medial and lateral knees, medial and lateral ankles, toe (second metatarsal head), heel, and lateral wands over the mid-femur and mid-tibia. To avoid excessive errors in hip joint calculation due to the adipose tissue of over-weight and obese participants, tie band was used in pelvic area, and the distance between left and right anterior superior iliac spines (ASIS) was measured manually. A Vicon 3D motion capture system with a 10-digital camera (Vicon 612 system, Oxford Metrics Ltd., Oxford, U.K.) measured the 3D locations of all markers on the landmarks of lower extremity segments (60 Hz sampling frequency). During the gait test, ground reaction forces were measured with two staggered AMTI force platforms (Advanced Mechanical Technologies, Inc., Watertown, MA, USA; 1080 Hz sampling frequency).

After all markers were positioned on the skin and non-reflective firm fitting spandex pants, participants were asked to walk across a 10-m long gait laboratory walkway at preferred speed and maximum speed. Participants were first asked to walk at their self-selected walking speed (like “walking in the street”) and to repeat the same task walking as fast as possible. Participants were not informed about the presence or location of force platforms on the walking path. Trials were performed until at least three complete gait cycles for both left and right sides with complete foot landing on the force platform for both the preferred speed and maximum speed tasks were obtained. The raw coordinate data of marker positions were digitally filtered with fourth-order zero-lag Butterworth filter with a cutoff at 6 Hz.

Data processing

Three dimensional (3D) kinematic and kinetic gait parameters measured and calculated in our gait laboratory protocol have been described in detail elsewhere (Ko et al., 2009). Briefly, mechanical joint powers of lower extremity rotations in the anterior-posterior (AP) and medial-lateral (ML) planes were calculated by using Visual3D (C-motion, Inc., Germantown, MD, USA). Bell pelvic model (using the left and right ASISs and PSISs) was used for hip joint calculation (Bell et al., 1990). Inertial properties of lower segments were estimated based on the anthropometric measurements (height and weight) and landmark locations (Hanavan, 1964). Based on kinematic measurements, ground reaction forces, and the paradigm of inverse dynamics, gait parameters in kinetics including joint moment and joint power were calculated. The mechanical work expenditures (MWEs) were calibrated by numeric integration of those mechanical joint powers during stance period using custom made software written by MATLAB (The MathWorks, Inc., Natick, MA, USA). To dissect functional differences of MWE in generative and absorptive modes, joint mechanical powers in positive (generative) and negative (absorptive) were integrated separately. In addition, to avoid direct weight effects on kinetic gait parameters, all MWEs were normalized by body mass. Spatiotemporal parameters including gait speed, stride length, and stride width were calculated in bundle by Visual3D, and manually checked by a technician using custom made software written in MATLAB. Gait periods including durations of stance, knee 1st flexion, and ankle 1st plantar flexion were calculated as proportions of duration time per one gait cycle (Fig. 1).

Statistical analysis

The characteristics of the study population are reported by BMI groups as mean values and standard deviations for continuous variables and proportions for categorical variables. The differences in characteristics as well as gait parameters at preferred and maximum gait speed across BMI categories were examined with generalized linear models (GLM). All the models were adjusted for gait speed (except gait speed itself), age, sex, and knee OA. To test for trend, categorical variables were entered in the GLM as ordinal variables. Statistical significance was

defined with p value less than 0.05. Statistical analyses were performed with SAS 9.1 Statistical Package (SAS Institute, Inc., Cary, North Carolina, USA).

RESULTS

Of the study participants, 34% were normal weight, 45 % overweight and 21 % obese. The average BMI was 26.8 kg/m^2 (ranges 19–39). Participant characteristics are summarized in Table 1 according to the BMI categories. The proportion of women was 68 % in the normal weight group, 42 % in the overweight group and 56 % in the obese group. Significant differences between groups were found for weight ($p < 0.001$), but not for the prevalence of knee OA ($p = 0.464$).

The gait parameters from the preferred and maximum speed walking according to the BMI categories are summarized in Table 2 and Table 3, respectively. Preferred gait speed was slower with increasing BMI (p for trend < 0.001) and obese had slower speed than normal weight participants ($p = 0.003$). Stride width was wider and the stance duration and ankle 1st plantar flexion duration (Fig. 1-a) were higher in obese participants compared to normal weight participants for the preferred speed walking ($p < 0.001$, for all). Range of rotational motions for lower extremity were different between obese and normal weight participants only for the hip in the ML plane in the preferred speed walking task ($p = 0.035$). No differences were found in joint peak moments from lower extremity in AP plane in the preferred walking speed task. Total ankle generative MWE in the AP plane was progressively and significantly lower with increasing BMI (p for trend 0.026) for the preferred speed walking. Compared to normal weight participants, obese participants had higher total ML MWEs in the knee (generative) and hip (absorptive) for the preferred speed walking ($p < 0.005$), and these increasing patterns from normal to obese participants also observed from overweight to obese participants ($p < 0.005$).

Interestingly, gait characteristics associated with obesity were slightly different in the maximum speed walking task. Gait speed was progressively lower with increasing BMI (p for trend 0.047), while no significant difference between groups was observed. Knee 1st flexion duration was higher for obese compared to normal weight participants ($p = 0.026$; Fig. 1-b). Total ankle absorptive MWE in the AP plane was lower with increasing BMI (p for trend 0.008). Finally, the difference in total ML knee MWE between BMI groups, which was observed from the preferred speed walking, was no longer detected in the maximum speed walking task.

DISCUSSION

The results of this study show that older adults with obesity modify their gait patterns compared to normal weight counterparts both while walking at preferred and maximum speed. To our knowledge, the present study is the first to examine the 3D kinematic and kinetic gait parameters of lower extremity in older individuals dispersed over a wide range of BMI.

Our findings are consistent with previous studies carried out in younger study populations, showing that obese persons tend to have slower gait speed, wider stride width, and longer stance duration while walking compared to normal weight persons (Lai et al., 2008; McGraw et al., 2000; Spyropoulos et al., 1991). In this older population, we also found elongation in the ankle 1st plantar flexion duration (for the walking at preferred and maximum speed) and knee 1st flexion duration (for only walking at maximum speed) among obese compared to non-obese participants. These findings suggest that in obese persons at the initial stage of stance (heel strike) elongated duration in ankle plantar flexion and knee flexion is meant to improve the absorption of additional impact imposed by heavier weight.

We also found that the total MWEs from the proximal joints of lower extremity in the AP and ML plane were different among obese participants compared to normal weight participants. Interestingly, after normalization by body weight, MWEs in the AP plane from lower extremity were similar in size between obese and normal weight participants except for the MWE in the ankle joint. Ankle generative MWE in the AP plane was lower for both walking test with increasing BMI, with significant group difference between obese and normal weight participants in the maximum-speed walking task. Reduced ankle mechanical joint power has been reported as one of the main gait characteristic of older adults for preferred speed walking (DeVita and Hortobagyi, 2000; Lewis and Ferris, 2008) and for maximum speed walking (Judge et al., 1996; Kerrigan et al., 1998). Contrary to mechanical joint power from previous studies, consumed mechanical work in ankle was not significantly associated with age in the present study, but it was associated with BMI. Obese people may have relatively less calf-muscle activity compared to normal weight persons, and therefore they generate less MWE from ankle while walking. Among older adults with obesity, the decrease in ankle mechanical work before toe-off phase is related to lower momentum production for the forward progression and may also have resulted increased ML mechanical energy usages, which was also seen in this study.

Contrary to findings in the AP plane, in the ML plane obese participants showed higher mechanical energy usages in hip and knee joints than non-obese participants. Higher ML knee generative MWE for preferred speed walking in obese and overweight participants may reflect increased ML activity in knee abduction during the stance phase, which may in turn, cause excessive movement in the medial femoral condyle, which may cause cartilage thinning and ultimately knee OA (Andriacchi et al., 2004). Increased ML hip MWE in obese participants for both walking tests was in absorptive mode, which may indicate activity in absorbing ML loading during stance phase. Mechanical joint power, which is the discrete value of MWE, is calculated by multiplication of angular velocity and joint moments. Considering that there was no difference in peak joint moment between groups, the increased ML absorptive hip MWE in obese participants may reflect a modified pattern of hip adduction in the ML plane which increased angular velocity (Fig. 2)

Another important finding of this study is the differences in gait pattern between normal weight, overweight and obese participants. Overweight participants had similar gait patterns with normal weight participants for all mechanical energy usages, while elongated gait phases such as ankle 1st plantar flexion duration and stance duration were more similar between overweight and obese participants in maximum-speed walking. Thus, it seems that spatiotemporal gait parameters are affected more easily by excess weight while changes in mechanical energy usage are present only among obese persons.

Our study has limitations that deserve discussion. We did not measure the metabolic energy consumption during gait analysis in the BLSA, so important information about efficiency in energy utilization in obese adults cannot be assessed. Second, the analysis in present study assumed symmetry during walking. To minimize the effect of this problem, participants with substantial mobility limitations were excluded from the study. In addition, the symmetry of gait cycle duration from the left and right sides was checked by examining the ratio between relatively slower and faster side, which was appeared to be close to 1 (0.96 ± 0.05). However, we acknowledge that subtle asymmetry of gait dynamics, which was not detectable in the clinical examination, may be of physiologic importance. Finally, even after extra efforts including manual ASIS width measure, tie band, and excluding participants with BMI over 40, excessive adipose tissue in the abdominal and pelvic area may have caused potential error in calculation of hip joint center (HJC) as reported also in a previous study (Cereatti et al., 2009).

In conclusion, older adults with obesity showed spatiotemporal gait patterns which allow longer initial rotations in the ankle and knee joints, thus may reduce impact on proximal joints of lower extremity imposed by additional body weight. In addition, obese persons had gait patterns of mechanical energy usages lower in AP plane in ankle and higher in ML plane in knee and hip, which may be disadvantageous in the efficiency of walking, considering that forward progression is the main goal of customary walking. Controlled weight loss among obese older persons may be beneficial in recovering normal gait pattern and reducing additional efforts in initial stance. Additional studies are needed to verify whether losing weight normalizes gait pattern characteristic of obese individuals.

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Figure 1.

Initial percentage gait cycles for the ankle plantar flexion (a) and knee 1st flexion (b) for normal weight and obese participants*.

(a) Ankle rotation for the maximum speed walking in the anterior-posterior plane

(b) Knee rotation for the maximum speed walking in the anterior-posterior plane

* These figures are from representative participants of normal weight and obese

Figure 2.

Joint angle and moment for the hip abduction and adduction in the medial-lateral (ML) plane which caused the absorptive ML hip mechanical power*.

* This figure is from one representative normal weight participant for the preferred speed walking

Table 1

Characteristics of the study population by Body Mass Index group^{*}.

Characteristics for participants	Mean (SE) and proportion				P values in group comparisons and chi-square		
	normal BMI < 25 (n = 56; 34 %)	overweight 25 ≤ BMI < 30 (n = 74; 45 %)	obese BMI ≥ 30 (n = 34; 21 %)	normal vs. overweight	normal vs. obese	overweight vs. obese	chi-square
Age, years	68.88 (1.14)	67.08 (0.99)	68.79 (1.47)	0.453	0.999	0.598	
Sex, women, %	68	42	56				
Height, meter	1.67 (0.01)	1.70 (0.01)	1.67 (0.02)	0.172	0.988	0.210	
Weight, kg	62.65 (1.27)	79.24 (1.10)	92.15 (1.64)	< 0.001	< 0.001	< 0.001	
Knee Osteoarthritis (OA), %	13	12	21				0.464

BMI = body mass index; SE = standard error

* Continuous variables are presented in mean (SE) and categorical variables in proportions

Table 2

Obesity-associated gait parameters for the preferred speed walking task.

Adjusted mean (SE) [†]								P values in group comparisons and trend	
Preferred speed walking task	normal BMI < 25 (n =56; 34 %)	overweight 25≤ BMI< 30 (n =74; 45 %)	obese BMI ≥ 30 (n =34; 21 %)	normal vs. overweight	normal vs. obese	overweight vs. obese	Trend with BMI		
Spatiotemporal									
Speed, m/s	1.20 (0.03)	1.13 (0.02)	1.06 (0.03)	0.119	0.003	0.172	<0.001		
Stride width, cm	10.02 (0.33)	10.62 (0.28)	12.40 (0.41)	0.360	<0.001	0.001	<0.001		
Stance, PGC	63.26 (0.20)	63.70 (0.17)	64.50 (0.25)	0.225	<0.001	0.024	<0.001		
Knee 1 st flexion, PGC	13.00 (0.19)	13.20 (0.16)	13.72 (0.24)	0.723	0.057	0.170	0.064		
Ankle 1 st plantar flexion, PGC	5.64 (0.19)	6.22 (0.16)	7.08 (0.24)	0.065	<0.001	0.009	<0.001		
In Anterior-posterior (AP) plane									
Range of rotation, degree									
Hip	39.35 (0.56)	40.69 (0.48)	40.02 (0.70)	0.176	0.748	0.705	0.234		
Knee	54.70 (0.74)	55.44 (0.63)	54.08 (0.92)	0.729	0.865	0.443	0.757		
Ankle	24.34 (0.51)	24.59 (0.44)	24.13 (0.64)	0.930	0.967	0.828	0.451		
Peak joint moment, N·m/kg									
Hip	1.24 (0.03)	1.27 (0.02)	1.33 (0.04)	0.718	0.153	0.389	0.053		
Knee	0.65 (0.02)	0.68 (0.02)	0.70 (0.03)	0.416	0.336	0.915	0.229		
Ankle	1.06 (0.03)	1.06 (0.03)	0.99 (0.04)	0.999	0.288	0.239	0.088		
Total generative MWE, 1000*J/kg									
Hip	195.21 (7.47)	198.72 (6.39)	182.80 (9.35)	0.934	0.565	0.340	0.145		
Knee	96.66 (5.37)	108.07 (4.58)	109.59 (6.71)	0.253	0.303	0.981	0.076		
Ankle	175.99 (6.21)	176.58 (5.31)	162.41 (7.77)	0.997	0.374	0.291	0.026		

Adjusted mean (SE) [†]								P values in group comparisons and trend	
Preferred speed walking task	normal BMI < 25 (n =56; 34 %)	overweight 25≤ BMI< 30 (n =74; 45 %)	obese BMI ≥ 30 (n =34; 21 %)	normal vs. overweight	normal vs. obese	overweight vs. obese	Trend with BMI		
Total absorptive MWE, 1000*J/kg									
Hip	245.91 (13.85)	253.00 (11.84)	284.49 (17.33)	0.922	0.204	0.294	0.052		
Knee	218.47 (9.39)	232.27 (8.02)	238.42 (11.74)	0.516	0.394	0.902	0.388		
Ankle	137.38 (7.09)	141.23 (6.06)	137.21 (8.87)	0.913	0.999	0.926	0.767		
In Medial-lateral (ML) plane									
Range of rotation, degree									
Hip	9.64 (0.30)	10.28 (0.26)	10.87 (0.38)	0.250	0.035	0.404	0.008		
Knee	10.82 (0.57)	10.65 (0.48)	11.47 (0.71)	0.971	0.759	0.599	0.701		
Ankle	9.39 (0.42)	8.52 (0.36)	8.97 (0.52)	0.270	0.811	0.760	0.253		
Peak joint moment, N·m/kg									
Hip	0.88 (0.01)	0.88 (0.01)	0.85 (0.02)	0.989	0.409	0.378	0.268		
Knee	0.47 (0.02)	0.43 (0.01)	0.46 (0.02)	0.251	0.980	0.454	0.685		
Ankle	0.17 (0.01)	0.17 (0.01)	0.15 (0.01)	0.999	0.028	0.017	0.024		
Total generative MWE, 1000*J/kg									
Hip	81.70 (3.95)	88.62 (3.37)	76.85 (4.94)	0.391	0.731	0.124	0.403		
Knee	9.71 (1.02)	10.39 (0.87)	15.54 (1.28)	0.871	0.002	0.003	0.002		
Ankle	9.11 (2.05)	13.28 (1.75)	6.63 (2.56)	0.284	0.737	0.085	0.275		
Total absorptive MWE, 1000*J/kg									
Hip	42.07 (2.92)	45.50 (2.49)	61.55 (3.65)	0.654	<0.001	0.001	<0.001		
Knee	24.49 (1.69)	23.19 (1.44)	20.08 (2.11)	0.832	0.247	0.447	0.015		
Ankle	18.20 (1.92)	20.11 (1.64)	15.81 (2.41)	0.738	0.727	0.306	0.356		
Others adjusted by speed, age, sex, and knee OA									

Others adjusted by speed, age, sex, and knee OA

BMI = body mass index; SE = standard error

PGC= proportion of gait cycle; MWE = mechanical work expenditure

[†] Speed adjusted by age, sex, and knee osteoarthritis (OA)

Table 3

Obesity-associated gait parameters for the maximum speed walking task.

Maximum speed walking task	Adjusted mean (SE) [†]				P values in group comparisons and trend			
	normal BMI < 25 (n = 54; 36 %)	overweight 25 ≤ BMI < 30 (n = 67; 44 %)	obese BMI ≥ 30 (n = 31; 20 %)		normal vs. overweight	normal vs. obese	overweight vs. obese	Trend with BMI
<i>Spatiotemporal</i>								
Speed, m/s	1.76 (0.04)	1.72 (0.03)	1.69 (0.05)		0.667	0.400	0.810	0.047
Stride width, cm	9.85 (0.33)	10.22 (0.30)	11.19 (0.44)		0.683	0.046	0.172	0.048
Stance, PGC	61.86 (0.15)	62.35 (0.13)	62.77 (0.20)		0.047	0.001	0.77	<0.001
Knee 1 st flexion, PGC	13.83 (0.25)	14.47 (0.22)	14.93 (0.33)		0.152	0.026	0.479	0.015
Ankle 1 st plantar flexion, PGC	4.50 (0.33)	5.67 (0.30)	5.93 (0.44)		0.026	0.027	0.877	<0.001
<i>In Anterior-posterior (AP) plane</i>								
Range of rotation, degree								
Hip	46.40 (0.71)	46.10 (0.64)	45.41 (0.94)		0.949	0.687	0.819	0.557
Knee	57.85 (0.79)	57.99 (0.71)	57.07 (1.05)		0.992	0.826	0.753	0.667
Ankle	25.27 (0.58)	24.62 (0.52)	24.15 (0.77)		0.690	0.485	0.869	0.131
<i>Peak joint moment, N·m/kg</i>								
Hip	1.74 (0.24)	2.15 (0.22)	1.73 (0.32)		0.425	0.999	0.518	0.998
Knee	1.04 (0.15)	1.26 (0.14)	0.95 (0.20)		0.529	0.933	0.406	0.689
Ankle	1.20 (0.06)	1.18 (0.05)	0.97 (0.08)		0.959	0.050	0.069	0.008
<i>Total generative MWE, 1000*J/kg</i>								
Hip	359.78 (13.47)	346.86 (12.10)	339.90 (17.86)		0.761	0.654	0.945	0.133
Knee	156.21 (8.95)	160.46 (8.03)	163.03 (11.86)		0.935	0.892	0.983	0.325
Ankle	266.44 (9.12)	245.45 (8.20)	214.96 (12.10)		0.213	0.003	0.098	<0.001

	Adjusted mean (SE) $\ddagger$			P values in group comparisons and trend		
	normal BMI < 25 (n = 54; 36 %)	overweight 25 ≤ BMI < 30 (n = 67; 44 %)	obese BMI ≥ 30 (n = 31; 20 %)	normal vs. overweight	normal vs. obese	overweight vs. obese
Maximum speed walking task						
Total absorptive MWE, 1000*J/kg						
Hip	330.85 (17.65)	322.20 (15.86)	369.95 (23.41)	0.931	0.386	0.215
Knee	324.24 (12.67)	336.93 (11.39)	352.42 (16.81)	0.743	0.383	0.728
Ankle	121.35 (7.65)	109.57 (6.87)	88.39 (10.15)	0.497	0.030	0.200
Trend with BMI						
						0.093
						0.090
						0.008
In Medial-lateral (ML) plane						
Range of rotation, degree						
Hip	12.05 (0.39)	12.50 (0.35)	13.54 (0.52)	0.672	0.063	0.228
Knee	10.35 (0.53)	10.33 (0.47)	11.90 (0.70)	0.999	0.189	0.154
Ankle	9.47 (0.46)	8.44 (0.42)	9.62 (0.61)	0.237	0.979	0.252
Trend with BMI						
						0.006
						0.357
						0.917
Peak joint moment, N-m/kg						
Hip	0.95 (0.02)	0.98 (0.02)	0.92 (0.03)	0.624	0.704	0.240
Knee	0.52 (0.02)	0.50 (0.02)	0.53 (0.03)	0.688	0.888	0.464
Ankle	0.20 (0.03)	0.23 (0.02)	0.16 (0.04)	0.746	0.569	0.217
Trend with BMI						
						0.533
						0.911
						0.469
Total generative MWE, 1000*J/kg						
Hip	84.64 (4.47)	88.69 (4.02)	81.06 (5.93)	0.784	0.882	0.539
Knee	15.67 (1.69)	15.68 (1.52)	20.28 (2.25)	0.999	0.239	0.213
Ankle	15.81 (1.93)	11.18 (1.74)	8.70 (2.56)	0.188	0.074	0.699
Trend with BMI						
						0.734
						0.204
						0.017
Total absorptive MWE, 1000*J/kg						
Hip	66.19 (4.72)	77.20 (4.25)	93.81 (6.27)	0.205	0.002	0.077
Knee	24.52 (2.00)	28.28 (1.79)	27.19 (2.65)	0.353	0.705	0.939
Ankle	24.58 (1.93)	23.61 (1.73)	22.15 (2.56)	0.928	0.733	0.884
Trend with BMI						
						<0.001
						0.952
						0.656

Others adjusted by speed, age, sex, and knee OA

BMI = body mass index; SE = standard error

PGC= proportion of gait cycle; MWE = mechanical work expenditure

[†] Speed adjusted by age, sex, and knee osteoarthritis (OA)