Relative Effort while Walking Is Higher among Women Who Are Obese, and Older Women

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ABSTRACT

KOUSHYAR, H., D. E. ANDERSON, M. A. NUSSBAUM, and M. L. MADIGAN. Relative Effort while Walking Is Higher among Women Who Are Obese, and Older Women. *Med. Sci. Sports Exerc.*, Vol. 52, No. 1, pp. 105–111, 2020. **Purpose:** Individuals who are obese, and older individuals, exhibit gait alterations that may result, in part, from walking with greater effort relative to their maximum strength capacity. The goal of this study was to investigate obesity-related and age-related differences in relative effort during gait. **Methods:** Four groups of women completed the study, including 10 younger healthy-weight, 10 younger obese, 10 older healthy-weight, and 9 older obese women. The protocol included strength measurements at the hip, knee, and ankle in both flexion and extension, and gait trials under self-selected and constrained (1.5 m·s^{-1} gait speed and 0.65-m step length) conditions. Relative effort was calculated as the ratio of joint torques during gait, and strength from a subject-specific model that predicted strength as a function of joint angle. **Results:** Relative effort during self-selected gait was higher among women who were obese in knee extension ($P = 0.028$) and ankle plantar flexion ($P = 0.013$). Although both joint torques and strength were higher among women who were obese, these increases in relative effort were attributed to greater obesity-related increases in joint torques than strength. Relative effort was also higher among older women in hip flexion ($P < 0.001$) and knee extension ($P = 0.008$), and attributed to age-related strength loss. Results were generally similar between self-selected and constrained gait, indicating the greater relative effort among women who were obese and older women was not attributed to differences in gait spatiotemporal characteristics. **Conclusions:** Women who were obese, as well as older women, walk with greater relative effort. These results may help explain the compromised walking ability among these individuals. **Key Words:** GAIT, STRENGTH, OBESITY, AGING

One-third of the adults in the United States are obese (1). Obesity is linked to a number of gait alterations, including slower gait speed (2,3), shorter step length (4), longer duration stance phase and double support (3,5,6), and difficulty walking long distances (7). Possible reasons for these gait alterations include range-of-motion limitations (3,6), knee extensor dysfunction (8), and neuromuscular adaptations to reduce energy expenditure (2,4), reduce knee joint loading (2,5,6), or maintain balance (3,4).

Another possible reason for obesity-related gait alterations is that individuals who are obese walk with greater relative effort. Relative effort has been calculated by expressing joint torques during an activity as a percentage of strength, or maximum voluntary torque (9–11). Relative effort during gait may be higher among individuals who are obese because they exhibit higher joint torques at the ankle (5,6), knee (5), and hip (5). Although lower limb strength is also higher among individuals who are obese in knee extension (12–14), hip flexion (13), and ankle dorsiflexion (13), relative effort may still be higher if obesity-related increases in joint torques surpass increases in strength. For example, Browning and Kram (5) reported a 51% obesity-related increase in peak knee extension torque during 1.5 m·s^{-1} gait, while Koushyar et al. (13) reported a 30% obesity-related increase in knee extension strength, which would together suggest an 11% obesity-related increase in knee extension relative effort during gait. Prior studies have quantified relative effort during sit-to-stand (9–11), stair ascent and descent (10,15), and gait (15–17). However, we are not aware of any studies that have investigated the effects of obesity on relative effort during gait. Identifying any such effects could help clarify the underlying factors by which obesity compromises walking ability and inform interventions to improve walking capacity among individuals who are obese.

Aging has also been associated with gait alterations, including a lower gait speed (18), shorter step length (16,18), and smaller ranges of motion at the ankle and hip (16,18). These alterations have been attributed, in part, to walking with greater relative effort (15,16). For example, Anderson and Madigan (16) reported relative effort of the ankle plantar flexors to be close to 100% among older adults walking at a hurried speed, indicating that

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Submitted for publication November 2018.
Accepted for publication July 2019.
Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.acsm-msse.org).

0195-9131/20/5201-0105/0
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DOI: 10.1249/MSS.0000000000002093

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near full effort was being exerted. Older adults who are obese would seem to be particularly susceptible to greater relative effort during gait due to obesity-related increases in joint torques, and age-related loss of strength (13,19).

The goal of this study was to investigate obesity-related and age-related differences in relative effort during the support phase of gait. We focused on women because they have a higher prevalence of obesity (1) and obesity-related mobility limitations (20) than men. We hypothesized that: 1) relative effort would be higher among women who were obese compared with healthy-weight women, 2) relative effort would be higher among older women compared with young women, and 3) obesity-related differences in relative effort would be larger among older women than young women. We evaluated subjects during self-selected gait, as well as during a constrained gait (fixed speed and step length across all subjects), due to the potential for obesity-related differences in gait characteristics from confounding any obesity-related differences in relative effort.

METHODS

Thirty-nine women were recruited to form four groups: 10 young (18–30 yr) healthy-weight (body mass index, 18–24.9 $kg \cdot m^{-2}$), 10 young obese (body mass index >30 $kg \cdot m^{-2}$), 10 older (65–80 yr) healthy-weight, and 9 older obese. A medical screening was used to exclude individuals with self-reported neurological, cardiac, or musculoskeletal conditions that affected balance or walking ability, or >2.3-kg change in body mass over the prior 6 months. Subjects also completed the Godin leisure-time exercise questionnaire (21) to quantify their physical activity level, which was viewed to potentially influence relative effort. Body fat percentage was estimated using a Lange skinfold caliper (Cambridge Scientific Industries, Cambridge, MA) and the manufacturer's recommended usage. All but one young healthy-weight and one older healthy-weight subject were right-foot dominant (preferred to kick a ball). The study was approved by the university institutional review board, and written informed consent was obtained from all subjects prior to participation.

Two experimental sessions were used to minimize potential fatigue development from completing all strength testing during a single session. In the first session, subjects completed all gait trials as described below, and knee strength measurements. In the second session, subjects completed ankle and hip strength measurements.

At the beginning of the first session, subjects donned compression shorts and walking shoes (same make/model for all subjects). All gait trials were performed along a 10-m level walkway, with self-selected trials performed before constrained gait trials. During self-selected trials, subjects were instructed to walk naturally and to look straight ahead. Up to seven practice trials were performed to acclimatize subjects to the experimental surroundings and to identify the proper starting position along the walkway so their right foot naturally and consistently landed on a force platform (Model 9090; Bertec Corporation, Columbus, OH) integrated into the middle of the walkway. Five trials were then performed with proper foot placement on the force platform. During constrained trials, mean speed during each trial was constrained to $1.5 \pm 0.05\ m \cdot s^{-1}$, via verbal feedback after each trial, and measured using a reflective marker on the subject's back. Step length was constrained to 0.65 m, by asking subjects to step on markings spaced at this distance along the walkway. The chosen speed and step length were intended as representative of self-selected values among young adults (18,22,23). Five constrained trials were performed.

After completing all gait trials in the first session, knee strength was measured in extension and flexion using a commercial dynamometer (System 3; Biodex Medical Systems, Inc., Shirley, NY). Measurements were collected from the right knee while in a seated position with the hip flexed 70°. Relaxed trials were first performed to measure the passive elastic/gravitational torque over the entire range of motion. During these trials, subjects were instructed to remain relaxed while the dynamometer attachment moved at $5° \cdot s^{-1}$ throughout their individual joint range of motion at least three times. Next, subjects performed isometric maximum voluntary contractions in knee extension and flexion at four joint angles individualized to each subject's ROM. We found the range of motion (max flexion to min flexion), subtracted 10° from it, and then divided that by 3. For example, if we consider the range of motion to be 130°, the difference in the angles would be (120/3 = 40°). The angles would be 5°, 45°, and 85°, and 125° knee flexion. For all strength measurements, one practice trial was performed first, followed by three actual trials with ~30 s of rest between trials. The actual trial with the highest torque was used for further analysis.

In the second session, ankle and hip strength in extension and flexion were measured. The testing protocol was similar to knee measurements, except for differences in posture. Ankle measurements were completed first while subjects were in a seated position, with the knee flexed 50° and the hip flexed 80°. Hip measurements were taken while subjects were in a standing position, using a custom setup (19), with the knee held near full extension by a knee immobilizer. A 10-min rest period was given between ankle and hip measurements.

Strength measurements were used to individualize joint-specific models of strength for each subject, and were then used to predict strength as a function of joint angle. By doing so, we accounted for known variations in strength with joint angle. During strength measurements, dynamometer attachment angle, angular velocity, and torque were sampled at 200 Hz and low-pass filtered at 5 Hz (fourth-order zero-phase shift Butterworth filter). Passive elastic and gravitational torque was estimated by fitting a line (least squares) to torque data from relaxed trials throughout the range of motion, and was subtracted from each maximum voluntary contraction trial (24) to find the active component of joint torque. Both active and passive components of the joint torque/strength measurements were used to model strength as a function of joint angle (19) for each joint (hip, knee, and ankle) and exertion (flexion and extension) combination.

During gait trials, ground reaction forces were sampled at 1000 Hz from the force platform, low-pass filtered at 40 Hz

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(fourth-order zero-phase-shift Butterworth filter), and down sampled to 100 Hz. Segmental kinematics were collected using reflective markers placed bilaterally at the acromion process, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, lateral femoral epicondyle, lateral malleolus, calcaneus, and head of the fifth metatarsal. In addition, clusters of three markers were placed mid-shank and mid-thigh. Markers positions were sampled at 100 Hz using a six-camera motion capture system (MX-T10; Vicon Motion Systems Inc., Los Angeles, CA) and low-pass filtered at 7 Hz (fourth-order zero-phase-shift Butterworth filter).

Sagittal plane joint torques were calculated at the ankle, knee, and hip using a two-dimensional inverse dynamics analysis and custom-written code (Matlab 2013a; The Mathworks Inc., Natick, MA). Segmental inertial parameters were estimated using established methods (25), and hip, knee, and ankle joint centers were identified using a functional approach (26). For each subject, one representative self-selected trial and one constrained trial was used for the analysis. The former was identified as having the minimum deviation from the subject's mean speed across their self-selected trials, and the latter as having the minimum deviation from the target speed (1.5 $m \cdot s^{-1}$). Relative effort at the ankle, knee, and hip was determined at each sample (100 Hz) during stance phase, as the ratio of the joint torque to strength, the latter being predicted from the aforementioned model of strength based on joint angle (16). For example, when knee torque indicated an extensor-dominant torque, relative effort was calculated using this torque value and the subject's knee extensor strength at the corresponding knee angle that was predicted by their individualized knee extensor strength model. The same approach was used to calculate relative effort at the hip and ankle using separate individualized strength models for these joints.

Two-way analyses of covariance were used to investigate differences in hip, knee, and ankle peak relative effort between obesity groups (healthy-weight or obese), age groups (young or older), and their interaction during the stance phase of gait. Godin scores of leisure time physical activity level were used as a covariate to account for variations in physical activity that may influence relative effort. To provide insight on potential mechanisms underlying any obesity or age-related differences in peak relative effort, we also performed an identical analysis on torque at peak relative effort (the numerator of the relative effort calculation), and strength at peak relative effort (the denominator of the relative effort calculation that was predicted by the strength model). Because we hypothesized (and anticipated) obesity–age interactions, we performed separate but identical analyses for self-selected and constrained trials to avoid three-way interactions that may have occurred if both gait conditions were included in the same analyses. In the event of a significant obesity–age interaction, *post hoc* tests were performed using Tukey's honestly significant difference test. Effect sizes were quantified using partial eta squared. Statistical analyses were performed using JMP Pro 13 (SAS Institute, Inc., Cary, NC) with a significance level of $P < 0.05$.

RESULTS

Body mass index and body fat were higher among women who were obese compared with healthy-weight women, and among older women compared with young women (Table 1). Results for self-selected gait are reported here, whereas those for constrained gait are available elsewhere for conciseness (see Document, Supplemental Digital Content 1, text summary and tables of results, http://links.lww.com/MSS/B690). Gait speed did not exhibit an obesity–age interaction, but did exhibit a main effect of obesity in that it was 0.10 $m \cdot s^{-1}$ slower among women who were obese. Step length did not exhibit an obesity–age interaction, or main effects of obesity or age (Table 2).

Relative effort exhibited similar time-varying trends over stance across subject groups (Fig. 1). Two local maxima/minima (i.e., peaks) occurred at the hip, four at the knee, and two at the ankle. These peaks were the focus of our analysis. Peak relative effort exhibited no obesity–age interactions, but did exhibit main effects of obesity and age (Table 2). Regarding main effects of obesity, peak relative effort among women who were obese was 23% higher in knee extension and 35% higher in ankle plantar flexion compared with healthy-weight women. Regarding main effects of age, peak relative effort among older women was 22% higher in hip flexion and 15% higher in knee extension compared with young women.

Joint torques also exhibited similar time-varying trends over stance across subject groups and exhibited the same local peaks as relative effort (Fig. 1). Joint torque at peak relative effort exhibited an obesity–age interaction for ankle plantar flexion torque (Table 3). This interaction was due to a 47.0-N·m obesity-related increase among young women, and a 27.5-N·m obesity-related increase among older women. Joint torque at peak relative

TABLE 1. Subject group characteristics, mean (standard deviation).

	Young and Healthy-Weight	Young and Obese	Older and Healthy-Weight	Older and Obese
N	10	10	10	9
Age (yr)	21.7 (3.3)	23.1 (3.8)	68.8 (5.5)	68.2 (4.2)
Height (cm)[a]	164.6 (4.3)	166.4 (6.1)	161.5 (6.3)	163.1 (5.0)
Body mass (kg)	60.9 (5.7)	93.3 (8.9)	59.2 (7.9)	86.4 (5.4)
BMI ($kg \cdot m^{-2}$)	22.5 (1.8)	33.7 (2.9)	22.7 (3.0)	32.5 (2.0)
Body fat (%)[b]	22.6 (1.6)	35.2 (2.5)	33.9 (4.3)	42.3 (2.4)
Godin score[c]	36.8 (16.9)	33.5 (20.6)	27.2 (15.2)	27.2 (13.8)

[a]Exhibited a main effect of age ($P = 0.034$), but not obesity ($P = 0.131$).
[b]Although the obesity–age interaction was significant ($P = 0.041$) due to a slightly higher obesity-related difference among young women compared to older women, % body fat was generally higher among women who were obese compared healthy-weight women, and higher among older women compared with young women.
[c]No obesity–age interaction, or main effects of obesity or age ($P > 0.05$).

TABLE 2. Gait characteristics and peak relative effort (% available strength) during self-selected gait, least squares means (SE).

	Healthy-Weight	Obese	Obesity, *P*	Young	Older	Age, *P*	Obesity–Age, *P*
Gait speed ($m \cdot s^{-1}$)	1.36 (0.03)	1.26 (0.03)	0.018	1.33 (0.03)	1.30 (0.03)	0.420	0.128
Step length (m)	0.71 (0.02)	0.69 (0.02)	0.583	0.71 (0.02)	0.69 (0.02)	0.424	0.921
HE1	47 (4)	51 (4)	0.517	45 (4)	52 (4)	0.251	0.985
HF1	69 (3)	70 (4)	0.819	58 (4)	80 (4)	<0.001	0.635
KF1	59 (6)	72 (7)	0.176	61 (7)	69 (7)	0.404	0.538
KE1	68 (7)	91 (7)	0.028	70 (7)	90 (7)	0.056	0.284
KF2	47 (6)	47 (7)	0.959	47 (6)	46 (6)	0.928	0.154
KE2	23 (3)	28 (4)	0.252	18 (4)	33 (4)	0.008	0.673
ADF1	52 (6)	56 (7)	0.721	49 (7)	58 (7)	0.374	0.683
APF1	128 (9)	163 (10)	0.013	149 (9)	142 (10)	0.627	0.510

Note: Healthy-weight and obese values are collapsed across age groups, and young and older values are collapsed across obesity groups.

effort also exhibited main effects of obesity and age. Regarding main effects of obesity, joint torque at peak relative effort among women who were obese was 20% to 24% higher at the hip, and 29% to 58% higher at the knee compared with healthy-weight women. Regarding the main effect of age, joint torque at peak relative effort among older women was 38% lower in knee flexion compared with young women.

Strength at peak relative effort exhibited no obesity–age interactions, but did exhibit main effects of obesity and age (Table 4). Regarding main effects of obesity, strength at peak relative effort among women who were obese was 17% to 18% higher at the hip, and 15% higher in ankle dorsiflexion compared with healthy-weight women. Regarding main effects of age, strength at peak relative effort among older women was 18% to 26% lower at the hip, 25% to 38% lower at the knee, and 20% lower in ankle dorsiflexion compared with young women.

Results from constrained gait were generally similar to those from self-selected gait, particularly for torque and strength at peak relative effort. Peak relative effort during both gait conditions was higher among women who were obese in ankle plantar flexion compared with healthy-weight women, and higher among older women in hip flexion and knee extension compared with young women. Torque at peak relative effort during both gait conditions was higher among women who were obese in hip extension and flexion, knee extension and flexion, and ankle plantar flexion. Torque at peak relative effort during both

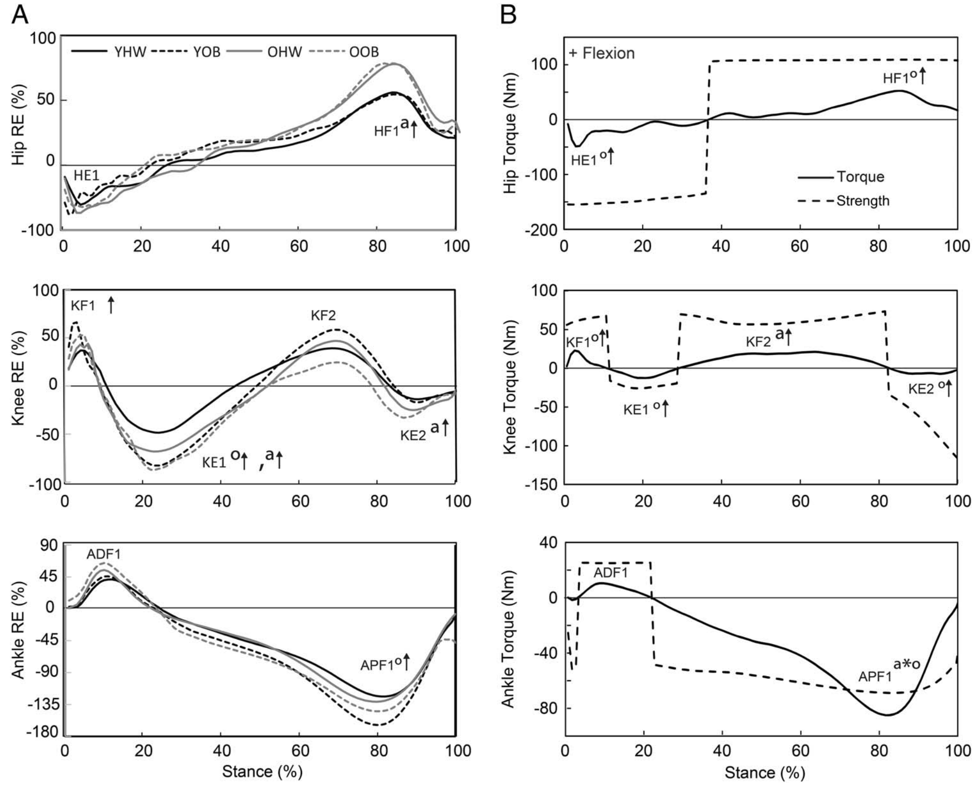

FIGURE 1—A, Ensemble averaged relative effort for each subject group over the normalized stance phase of self-selected gait. B, Representative joint torque and available strength from a single subject over the normalized stance phase of self-selected gait. Positive values indicate flexor dominance, and negative values indicate extensor dominance. The symbol "o" indicates a statistically significant (*P* < 0.05) main effect of obesity, "a" indicates a main effect of age, and "a*o" indicates an interaction effect. *Up arrows* indicate higher among women who were obese compared with healthy-weight women, or higher among older than young women. *Down arrows* indicate lower among women who were obese compared with healthy-weight women, or lower among older than young women. Each localized peak is labeled with a unique abbreviation identifier that is used in subsequent tables: HE, hip extension; HF, hip flexion; KF, knee flexion; KE, knee extension; ADF, ankle dorsiflexion; APF, ankle plantar flexion.

TABLE 3. Joint torque at peak relative effort (N·m) during self-selected gait [least squares means (SE)].

	Healthy-Weight	Obese	Obesity, *P*	Young	Older	Age, *P*	Obesity–Age, *P*
HE1	49.5 (3.5)	61.3 (3.8)	0.030	56.6 (3.7)	54.1 (3.8)	0.656	0.816
HF1	55.4 (2.4)	66.4 (2.6)	0.004	60.6 (2.5)	61.2 (2.6)	0.886	0.579
KF1	24.4 (1.4)	31.4 (1.6)	0.002	29.0 (1.5)	26.9 (1.5)	0.350	0.813
KE1	33.0 (4.0)	55.6 (4.2)	<0.001	44.2 (4.1)	44.5 (4.3)	0.966	0.089
KF2	19.1 (2.8)	20.6 (3.1)	0.722	24.5 (2.9)	15.3 (3.1)	0.041	0.268
KE2	12.3 (1.7)	19.4 (1.8)	0.008	15.4 (1.8)	16.4 (1.8)	0.674	0.942
ADF1	13.5 (1.7)	16.3 (1.8)	0.275	15.4 (1.8)	14.5 (1.8)	0.734	0.433
APF1	89.8 (3.0)	127.0 (3.3)	<0.001*	118.0 (3.2)	98.7 (3.3)	<0.001*	0.037*

Note: Healthy-weight and Obese values are collapsed across age groups, and Young and Older values are collapsed across obesity groups.
*APF1 exhibited an obesity–age interaction effect in that obesity-related increases where larger among young than older women ($P < 0.05$).

gait conditions was also lower older women in ankle plantar flexion compared with young women. Strength at peak relative effort during both gait conditions was higher among women who were obese in hip flexion and ankle dorsiflexion compared with healthy-weight women, and lower among older women in hip extension and flexion, knee extension, and ankle dorsiflexion compared with young women. Results are summarized, and effect sizes are reported, for self-selected gait in Table 5, and for constrained gait in Table S4, http://links.lww.com/MSS/B690.

DISCUSSION

The goal of this study was to investigate obesity-related and age-related differences in relative effort during the support phase of gait. Our first hypothesis was that relative effort would be higher among women who were obese compared with healthy-weight women. This hypothesis was supported because peak relative effort was 20% to 48% higher among women who were obese in hip flexion, knee flexion, knee extension, and ankle plantar flexion. This greater relative effort appeared to generally result from joint torques exhibiting greater obesity-related increases than strength (Tables 5 and S4, http://links.lww.com/MSS/B690). Our second hypothesis was that relative effort would be higher among older women compared with young women. This hypothesis was supported because relative effort was higher among older women in hip flexion and knee extension. In contrast to obesity-related increases in relative effort, age-related increases in relative effort seemed to generally result from age-related reductions in strength at peak relative effort, and less due to age-related differences in joint torques. Our third hypothesis was that obesity-related differences in relative effort would be larger among older women than young women. This hypothesis was not supported because peak relative effort did not exhibit any obesity–age interaction effects. Given that obesity-related differences during constrained gait, when speed and step length were fixed, were generally similar as during self-selected gait, the greater relative effort among women who were obese was not attributed to differences in these gait characteristics. Overall, our results suggest that women who are obese use a greater proportion of their strength while walking than healthy-weight women, and this obesity-related effect occurred similarly among young and older women.

Several limitations to this study should be noted. Relative effort exceeded 100% for 62 of 296 (21%) peak relative effort values estimated during self-selected gait. Most of these were for ankle plantar flexion (58%) and knee extension (18%). Several sources of error may have contributed. First, the torque-producing capability of biarticular muscles (e.g., gastrocnemius) is dependent upon kinematics at both spanned joints (e.g., ankle and knee), yet the models we used to predict strength only accounted for kinematics at one joint (e.g., ankle). Second, inaccuracies in joint torque estimates using a two-dimensional inverse dynamics analyses, such as those resulting from the use of segment inertial estimates and skin surface markers to represent joint axes. Third, inaccuracies in strength measurements, such as those resulting from misalignment between axis of rotation of dynamometer and joint and submaximal effort. The consequence of relative effort exceeding 100% was that the relative effort at which strength was fully utilized was unclear. Nevertheless, relative effort still provided a quantitative measure of effort relative to maximum capacity, and thus is still considered relevant to evaluate obesity-related differences. Another limitation of our methodology was that we did not account for the effects of joint angular velocity on strength in our strength models that were used to estimate relative effort. We chose this approach because our initial attempts to account for both seemed overly sensitive to joint angular

TABLE 4. Strength at peak relative effort (N·m) during self-selected gait [least squares means (SE)].

	Healthy-Weight	Obese	Obesity, *P*	Young	Older	Age, *P*	Obesity–Age, *P*
HE1	110.6 (6.2)	129.8 (7.0)	0.049	132.0 (6.7)	108.4 (6.7)	0.020	0.872
HF1	86.3 (3.9)	102.0 (4.4)	0.012	108.2 (4.2)	80.1 (4.2)	<0.001	0.112
KF1	44.8 (3.2)	50.0 (3.5)	0.277	52.2 (3.4)	42.6 (3.5)	0.059	0.270
KE1	51.6 (4.9)	65.6 (5.2)	0.060	65.0 (5.0)	52.2 (5.3)	0.095	0.570
KF2	44.6 (3.6)	53.6 (4.0)	0.100	56.1 (3.7)	42.1 (4.0)	0.016	0.335
KE2	69.5 (6.9)	85.4 (7.5)	0.128	95.7 (7.2)	59.2 (7.4)	0.002	0.909
ADF1	26.4 (1.2)	30.3 (1.3)	0.028	31.5 (1.2)	25.2 (1.2)	0.001	0.137
APF1	73.2 (4.5)	82.8 (4.8)	0.152	83.3 (4.6)	72.8 (4.8)	0.132	0.864

Note: Healthy-weight and obese values are collapsed across age groups, and young and older values are collapsed across obesity groups.

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TABLE 5. Effect sizes (partial eta squared) for peak relative effort, torque at peak relative effort, and strength at peak relative effort during self-selected gait.

	Peak Relative Effort		Torque at Peak Relative Effort		Strength at Peak Relative Effort	
Group	Obese	Older	Obese	Older	Obese	Older
HE1	0.014	0.042	0.139↑	0.006	0.119↑	0.163↓
HF1	0.002	0.353↑	0.231↑	<0.001	0.188↑	0.417↓
KF1	0.057	0.022	0.256↑	0.027	0.037	0.107
KE1	0.147↑	0.113	0.327↑	<0.001	0.110	0.087
KF2	<0.001	<0.001	0.004	0.129↓	0.085	0.173↓
KE2	0.041	0.201↑	0.203↑	0.006	0.071	0.275↓
ADF1	0.004	0.025	0.037	0.004	0.142↑	0.286↓
APF1	0.179↑	0.008	0.685[a]↑	0.354[a]↓	0.063	0.070

Healthy-weight and young subjects were used as basis for effect sizes. Up arrows indicate higher among women who were obese, or among older women ($P < 0.05$). Down arrows indicate lower among women who were obese, or older women ($P < 0.05$).
[a]An obesity–age interaction effect, yet higher among women who were obese for both older and young groups.

velocity, particularly for higher velocities at which our strength model predicted a relatively small strength value. Lastly, as with any cross-sectional experimental design, differences between subject groups other than obesity and age may have contributed to the differences identified.

Some differences in relative effort are apparent between the current values and those reported elsewhere. Peak relative effort among young adults found here during self-selected gait was consistently higher than values reported elsewhere. In particular, mean peak relative effort in hip extension was 42% here versus 30% elsewhere (16,17), in hip flexion was 57% here and ~30% elsewhere (16), and in ankle plantar flexion was 124% here and 58% to 86% elsewhere (16,17). By contrast, peak relative effort among older adults found here during self-selected gait was generally lower than values reported by Samuel et al. (15) In particular, mean peak relative effort for hip extension was 51% here and 127% elsewhere, for hip flexion was 80% here and 68% elsewhere (15), for knee flexion was 58% here and 75% elsewhere (15), and for knee extension was 88% here and 101% elsewhere (15). These differences in peak relative effort between studies were likely due to methodological differences, including differences in gait speed, subject sex distributions, strength measuring protocols, and methods to account for the effects of joint angle and angular velocity on strength.

Obesity and age-related increases in relative effort occurred at important times during the gait cycle when mechanical energy is being generated. For example, the ankle plantar flexors provide support and propulsion during push-off (27,28) during late stance and produce over two thirds of the total mechanical energy generation by the lower extremities during a gait cycle (6). The hip flexors generate mechanical energy during late stance and early swing. Moreover, increasing gait speed requires an increase in mechanical energy generation in hip flexion, ankle plantar flexion, knee flexion, and knee extension (29).

Walking with greater relative effort can compromise walking in multiple ways, even if relative effort does not reach its theoretical maximum. First, given that joint torques (and therefore relative effort) increase as gait speed increases (5), walking with greater relative effort suggests less reserve capacity to increase gait speed, or to perhaps execute a rapid stepping response to prevent a fall after balance perturbations such as tripping or slipping. Second, walking with greater relative effort can result in earlier fatigue (10,30), which may, at least partly, explain why individuals who are obese adopt a slower gait speed and have greater self-reported difficulty in walking longer distances (2,7). Third, a higher level of muscle force exertion than may occur with greater relative effort can increase in muscle force variability (31,32). Such variability has been considered as deleterious noise in the neuromuscular system (33) that can lead to undesirable inaccuracies in goal-oriented movements (34,35). Our results therefore provide mechanistic support of the potential limiting effect of strength on gait among women who are obese.

CONCLUSIONS

Women who were obese walked with greater relative effort than healthy-weight women. Although both joint torques and strength were higher among women who were obese, the greater relative effort was attributed to greater obesity-related increases in joint torques than strength. Additionally, older women walked with greater relative effort than young women, with these age-related increase generally resulting from age-related reductions in strength and not age-related increases in joint torques. These results may help to explain the compromised walking ability among women who are obese, as well as among older women.

This work was supported by award R01OH009880 from the Centers for Disease Control and Prevention (CDC). The contents of this article are solely the responsibility of the authors, and do not necessarily represent the official views of CDC.

Conflict of Interest: The authors have no conflicts of interest to report. The results of the present study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. In addition, these results do not constitute endorsement by ACSM.

REFERENCES

1. Ogden CL, Carroll MD, Kit BK, Flegal KM. Prevalence of childhood and adult obesity in the United States, 2011–2012. *JAMA*. 2014; 311(8):806–14.
2. Lai PP, Leung AK, Li AN, Zhang M. Three-dimensional gait analysis of obese adults. *Clin Biomech (Bristol, Avon)*. 2008;23(1 Suppl): S2–6.

3. Spyropoulos P, Pisciotta JC, Pavlou KN, Cairns MA, Simon SR. Biomechanical gait analysis in obese men. *Arch Phys Med Rehabil*. 1991;72(13):1065–70.
4. Page Glave A, Di Brezzo R, Applegate D, Olson JM. The effects of obesity classification method on select kinematic gait variables in adult females. *J Sports Med Phys Fitness*. 2014;54(2):197–202.
5. Browning RC, Kram R. Effects of obesity on the biomechanics of walking at different speeds. *Med Sci Sports Exerc*. 2007;39(9):1632.
6. DeVita P, Hortobágyi T. Obesity is not associated with increased knee joint torque and power during level walking. *J Biomech*. 2003;36(9):1355–62.
7. Stenholm S, Rantanen T, Alanen E, Reunanen A, Sainio P, Koskinen S. Obesity history as a predictor of walking limitation at old age. *Obesity*. 2007;15(4):929–38.
8. Vakula MN, Fisher KL, Garcia SA, et al. Quadriceps impairment is associated with gait mechanics in young adults with obesity. *Med Sci Sports Exerc*. 2019;51(5):951–61.
9. Bieryla KA, Anderson DE, Madigan ML. Estimations of relative effort during sit-to-stand increase when accounting for variations in maximum voluntary torque with joint angle and angular velocity. *J Electromyogr Kinesiol*. 2009;19(1):139–44.
10. Hortobágyi T, Mizelle C, Beam S, DeVita P. Old adults perform activities of daily living near their maximal capabilities. *J Gerontol A Biol Sci Med Sci*. 2003;58(5):M453–60.
11. Ioannis S, Poluxeni L, Themistoklis T, Savvas L, Dimitrios T, Vasileios S. Relative effort changes during sit to stand and stand to sit transition following muscle damage. *Med Sport J Rom Sports Med Soc*. 2014;10(4):2418.
12. Capodaglio P, Vismara L, Menegoni F, Baccalaro G, Galli M, Grugni G. Strength characterization of knee flexor and extensor muscles in Prader-Willi and obese patients. *BMC Musculoskelet Disord*. 2009;10(1):47.
13. Koushyar H, Nussbaum MA, Davy KP, Madigan ML. Relative strength at the hip, knee, and ankle is lower among younger and older females who are obese. *J Geriatr Phys Ther*. 2017;40(3):143–9.
14. Lafortuna CL, Maffiuletti NA, Agosti F, Sartorio A. Gender variations of body composition, muscle strength and power output in morbid obesity. *Int J Obes Relat Metab Disord*. 2005;29(7):833–41.
15. Samuel D, Rowe P, Nicol A. The functional demand (FD) placed on the knee and hip of older adults during everyday activities. *Arch Gerontol Geriatr*. 2013;57(2):192–7.
16. Anderson DE, Madigan ML. Healthy older adults have insufficient hip range of motion and plantar flexor strength to walk like healthy young adults. *J Biomech*. 2014;47(5):1104–9.
17. Requião LF, Nadeau S, Milot MH, Gravel D, Bourbonnais D, Gagnon D. Quantification of level of effort at the plantarflexors and hip extensors and flexor muscles in healthy subjects walking at different cadences. *J Electromyogr Kinesiol*. 2005;15(4):393–405.
18. Kerrigan DC, Todd MK, Della Croce U, Lipsitz LA, Collins JJ. Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments. *Arch Phys Med Rehabil*. 1998;79(3):317–22.
19. Anderson DE, Madigan ML, Nussbaum MA. Maximum voluntary joint torque as a function of joint angle and angular velocity: model development and application to the lower limb. *J Biomech*. 2007; 40(14):3105–13.
20. Vincent HK, Vincent KR, Lamb KM. Obesity and mobility disability in the older adult. *Obes Rev*. 2010;11(8):568–79.
21. Godin G, Shephard R. Godin leisure-time exercise questionnaire. *Med Sci Sports Exerc*. 1997;29(6s):S36.
22. Judge JO, Davis RB 3rd, Ounpuu S. Step length reductions in advanced age: the role of ankle and hip kinetics. *J Gerontol A Biol Sci Med Sci*. 1996;51(6):M303–12.
23. Silder A, Heiderscheit B, Thelen DG. Active and passive contributions to joint kinetics during walking in older adults. *J Biomech*. 2008; 41(7):1520–7.
24. Anderson DE, Nussbaum MA, Madigan ML. A new method for gravity correction of dynamometer data and determining passive elastic moments at the joint. *J Biomech*. 2010;43(6):1220–3.
25. Pavol MJ, Owings TM, Grabiner MD. Body segment inertial parameter estimation for the general population of older adults. *J Biomech*. 2002;35(5):707–12.
26. Piazza SJ, Erdemir A, Okita N, Cavanagh PR. Assessment of the functional method of hip joint center location subject to reduced range of hip motion. *J Biomech*. 2004;37(3):349–56.
27. Kepple TM, Siegel KL, Stanhope SJ. Relative contributions of the lower extremity joint moments to forward progression and support during gait. *Gait Posture*. 1997;6(1):1–8.
28. Sadeghi H, Sadeghi S, Prince F, Allard P, Labelle H, Vaughan CL. Functional roles of ankle and hip sagittal muscle moments in able-bodied gait. *Clinical Biomechanics*. 2001;16(8):688–95.
29. Cofré LE, Lythgo N, Morgan D, Galea MP. Aging modifies joint power and work when gait speeds are matched. *Gait Posture*. 2011; 33(3):484–9.
30. Lerner ZF, Board WJ, Browning RC. Effects of obesity on lower extremity muscle function during walking at two speeds. *Gait Posture*. 2014;39(3):978–84.
31. Carlton LG, Newell KM. Force variability and characteristics of force production. In Newell KM, Corcos, DM, editors. *Variability and Motor Control*. Champaign, IL: Human Kinetics; 1993. pp. 15–36.
32. Christou EA, Grossman M, Carlton LG. Modeling variability of force during isometric contractions of the quadriceps femoris. *J Mot Behav*. 2002;34(1):67–81.
33. Sherwood DE, Schmidt RA, Walter CB. The force/force-variability relationship under controlled temporal conditions. *J Mot Behav*. 1988;20(2):106–16.
34. Meyer DE, Smith J, Wright CE. Models for the speed and accuracy of aimed movements. *Psychol Rev*. 1982;89(5):449.
35. Schmidt RA, Zelaznik HN, Frank JS. Sources of inaccuracy in rapid movement. In: Stelmach GE, editor. *Information Processing in Motor Control and Learning*. New York, NY: Academic Press; 1978. pp. 183–203.