



Increasing Trunk Mass Evokes Lower Extremity Biomechanical Plasticity during Stair Descent

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ABSTRACT

International Journal of Exercise Science 16(1): 942-953, 2023. The purpose of this study was to investigate the influence of simulated changes in body mass on lower extremity joint work and relative joint contributions during stair descent. Ten healthy recreationally active college-age participants performed five stair descent trials in each of five loading conditions: no added load and with an additional 5%, 10%, 15% and 20% of their body weight. Three-dimensional ankle, knee and hip joint powers were calculated using a six degree-of-freedom model in Visual3D (C-Motion Inc., Germantown, MD, USA). Sagittal plane joint work was calculated as the joint power curve integrated with respect to time during the period between initial contact and toe off. Prism 9.0 (GraphPad Inc., San Diego, CA) was used to perform univariate 1 x 5 repeated measures analyses of variance to determine the effect of added mass on absolute and relative joint work values for total and for each lower extremity joint independently. Increasing added mass was associated with greater total lower extremity negative work during the stair descent task ($p < 0.001$). At the ankle, increasing added mass was associated with increasing magnitudes of negative joint work. Increasing added mass was associated with greater relative contributions of the ankle and reduced knee contributions to total negative lower extremity joint work ($p = 0.014$ and $p = 0.006$). The current findings demonstrated increases in ankle joint contributions to total lower extremity work while knee joint contributions to total lower extremity work were reduced in response to increasing added mass.

KEY WORDS: Added mass, stair descent, joint works, relative joint work contributions

INTRODUCTION

Osteoarthritis (OA) is a leading cause of joint pain and disability in the United States (24, 38). One of the most common sites of OA development is the knee joint (15). Clinically and economically knee OA may be the most impactful on society where patients experience almost twice the medical costs compared to healthy sex-and age-matched controls (25, 40). Due to

advancing age and increasing average body mass index of the US population, the prevalence of knee OA and knee replacement surgery is anticipated to increase (20, 19, 22, 34).

Obesity is the most common preventable risk factor influencing the development of OA. In the United States, approximately 41% of adults are overweight or obese while nearly 20% of children are classified as obese (8). Obesity is strongly correlated with declines in knee joint health and an increased risk of developing knee OA (9, 13, 36). In addition to cellular factors, obesity is associated with substantially greater joint loads underlying accelerated cartilage wear and joint degeneration (14). Individuals who are obese and have knee pain are much more likely to succumb to a knee replacement even if they lose weight (33). Advancing cartilage degeneration gives rise to skeletal involvement and degeneration of the bony structures of the joint yielding OA (14).

Knee joint loads during locomotion are proportional to body mass (4). As such, with an increase in body mass, there is a subsequent increase in knee joint loads. The greater joint loads associated with obesity are coupled with a proximal-to-distal shift in joint contributions to locomotion with reduced reliance on knee joint work and greater reliance on ankle joint work, a trend that is not observed in healthy participants (12). A proposed method to prevent or delay the progression of knee OA is weight loss (17, 29). Weight loss has been shown to disproportionately reduce knee joint loads when compared to magnitude of weight loss (29). Messier et al. (2005) demonstrated a 4:1 ratio of reductions in knee joint compressive forces relative to the amount of weight lost during overground walking. The weight loss-induced reductions in knee joint compressive forces are clinically relevant and have been suggested to slow the rate of development and progression of OA (1, 30).

Joint work is an alternative metric of joint load that also provides insight toward the neuromuscular strategy selected to complete a given task. Joint work, calculated as the joint power integrated with respect to time, represents the interaction of the task-specific mechanical demand and the joint kinetic pattern implemented to complete the task (5, 7, 10-12). Joint work has been used previously to infer upon differences in energy absorption or transfer (6), metabolic cost versus mechanical demand (5), and modulated neuromuscular strategies (32). Task-specific mechanical demand is known to increase with greater body mass, and joint work has been used to quantify differences in lower extremity biomechanics and neuromuscular strategy in obese compared to non-obese adults (12). While absolute joint work is a measure of lower extremity kinetics, relative joint work reflects the contributions of each joint and provides insight to the neuromuscular strategy selected to complete a given task (37). While a number of research studies have investigated the influence of increasing and decreasing body mass on lower extremity biomechanics including joint work and relative joint contributions, these studies have focused on overground or treadmill walking (1, 18, 30). No previous investigation has evaluated the mass-related changes in lower extremity joint work or relative joint contributions to stair negotiation.

Stair negotiation (ascent and descent) is a common activity of daily living which is understudied. Compared to walking, the knee experiences up to three times greater joint moments during stair

descent compared to overground walking (2). During stair descent, muscles perform eccentric contractions to absorb kinetic energy and prevent limb collapse. Therefore, a stair descent movement will be dominated by negative joint work values compared to overground walking in which the sum of positive and negative joint work values will approach zero due to the concentric propulsive phase of gait (27). Further, stair descent is typically associated with greater loading ranges and greater magnitudes of skeletal load when compared to level walking (23, 35).

The influence of body mass on lower extremity biomechanics during stair descent is not well understood. Based on previous findings in overground locomotion, it is anticipated that greater body mass values would be associated with greater lower extremity joint kinetics including ankle and knee joint work. Therefore, the purpose of this study was to investigate the influence of simulated changes in body mass on lower extremity joint work and relative joint contributions during a stair descent task. It was hypothesized that increases in added mass to the trunk would be associated with increases in ankle and knee joint work values. Supported by previous literature, it was further hypothesized that ankle joint relative contributions to total lower extremity work would increase while knee joint relative contributions to total lower extremity work would decrease with increases in added mass to the trunk.

METHODS

Participants

An *a priori* power analysis (G*Power 3.1.5) was conducted based on preliminary data using an effect size of 0.40, an alpha level of 0.05 and a power ($1-\beta$) of 0.80. The power analysis revealed that nine participants were required to sufficiently power this investigation. A sample of convenience of ten healthy, recreationally active college-aged participants were recruited for the current study. Recreationally active was functionally defined as the participant performing 30 minutes of exercise three or more times per week at moderate to vigorous intensity. Participants were excluded from the study if they had a current or recent (within 6 weeks) history of lower extremity injury or a history of major lower extremity surgery (i.e. total joint arthroscopy, ACL reconstruction, etc.). In accordance with the Helsinki Declaration, the study protocol was approved by the University of Memphis Institutional Review Board and all participants provided written informed consent prior to participation in this study. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (31). Prior to any testing, anthropometrics were recorded of height and weight and utilized to calculate the appropriate weight for the loading conditions (Table 1).

Table 1. Participant Characteristics.

Variables	Male	Female
<i>n</i>	6	4
Height (m)	1.79 ± 0.09	1.65 ± 0.04
Mass (kg)	84.58 ± 8.94	59.18 ± 4.95

Values recorded as mean ± SD.

Protocol

Each participant performed five stair descent trials in each of five loading conditions. Experimental conditions included the participant descending a set of instrumented stairs with no added load (BW) and with an additional 5% (BW5), 10% (BW10), 15% (BW15) and 20% (BW20) of their body weight added using a weighted vest and metal plates (Rogue Fitness, Columbus, OH). The weight vest had internally fitted and secured metal plates with varying loads to reach the required added load for each participant-loading condition combination. Loading conditions were presented in a randomized order to reduce systematic effects of learning and fatigue. Participants were provided several minutes of practice prior to testing to familiarize themselves to the load. Participants were instructed to begin the stair descent task with their left foot to ensure that the limb of interest (right limb) struck the embedded force platform. The initial left footstep was taken on the top level of the platform with the subsequent right step (the step of interest) being the first step in stair descent (Figure 1).

The staircase consisted of three steps and a handrail with the following dimensions: step rise, 18 cm; step width, 46 cm; step tread, 28 cm; stairway rise angle, 32.73 degrees (Figure 1). Participants were instructed not to use the handrail while performing stair negotiation. If a participant used the handrail, the trial was discarded and recollected. All participants completed five successful trials at a self-selected pace in each loading condition.



Figure 1. Images of the instrumented stair way and platform.

Three-dimensional kinematics and ground reaction forces (GRFs) were recorded simultaneously using an 18-camera motion capture system (240 Hz, Vicon Motion Systems, Ltd., Oxford, UK) and force platform (960 Hz, OR-7, AMTI, Watertown, MA), respectively. The skeleton was modeled using 14-mm retroreflective markers and included the trunk and pelvis as well as right and left thigh shank and foot segments. Anatomical markers to define the trunk were placed over the right and left acromion processes and the right and left anterior and

posterior superior iliac spines (ASIS and PSIS). The trunk was tracked using five individual retroreflective markers placed over the spinous process of the seventh cervical vertebra (C7), the spinous process of the tenth thoracic vertebra (T10), inferior angle of the right scapula, jugular notch and xiphoid process. The pelvis was defined and tracked using individual retroreflective markers placed over the anterior and posterior superior iliac spines as well as the right and left greater trochanters. Anatomical markers were also placed on the medial and lateral femoral epicondyles, medial and lateral malleoli and first and fifth metatarsal heads for each lower limb. The hip joint center was defined as previously described (3). Retroreflective markers placed on rigid clusters were used to track the right and left thigh and shank while the foot was tracked using four individual retroreflective markers placed over the posterior and lateral heel counter of the participant's shoe. After a standing calibration, all anatomical markers were removed leaving only tracking markers for the trunk and pelvis as well as the right and left thigh, shank and foot.

Data Analysis: Kinematic and GRF data were filtered using a fourth-order, zero-lag lowpass Butterworth filter with cutoff frequencies of 10 Hz and 50 Hz, respectively. Stair descent biomechanics were analyzed from initial contact (IC) to toe off (TO). IC was defined as the instant at which the vertical GRF exceeded a threshold of 20 N and remained above threshold for a period of at least 0.03 s. TO was defined as the instant at which the vertical GRF decreased below a threshold of 20 N and remained below threshold for a period of at least 0.03 s.

Three-dimensional ankle, knee and hip joint powers were calculated using a six degree-of-freedom model in Visual3D (C-Motion Inc., Germantown, MD, USA). Sagittal plane joint work was calculated as the joint power curve integrated with respect to time during the period between IC and TO. The current study focused on the contributions to load attenuation during stair descent and thus only periods of negative joint power were included in the joint work analysis. Total lower extremity negative joint work was calculated as the sum of the ankle, knee and hip joint work values. Relative joint contributions of the ankle, knee and hip joints to stair descent were calculated as the quotient of the individual joint work divided by the total lower extremity negative joint work. Subject means were calculated as the average of the five trials from each individual.

Statistical Analysis

Prism 9.0 (GraphPad Inc., San Diego, CA) was used to perform univariate 1 × 5 repeated measures analyses of variance (ANOVAs) to determine the effect of added mass on absolute and relative joint work values for each lower extremity joint (ankle, knee and hip) independently as well as for total lower extremity work. In the presence of a main effect of condition, post-hoc t-tests were performed to identify the source of the main effect of condition.

RESULTS

Increasing added mass was associated with greater total lower extremity negative work during the stair descent task ($p < 0.001$, $F = 6.8$, Table 2). Pairwise comparisons revealed that total lower

extremity work was smaller in the BW condition than all other conditions (+5%: $p = 0.039$; +10%: $p = 0.001$; +15%: $p = 0.001$; +20%: $p < 0.001$). Further, the +5% condition was associated with smaller total lower extremity work than the +20% condition ($p = 0.011$).

At the ankle, increasing added mass was associated with increasing magnitudes of negative joint work ($p < 0.001$, $F = 11.7$; Figure 2A, Table 2). Pairwise comparisons revealed that negative ankle joint work was greater in added load conditions compared to the BW condition (+5%: $p = 0.018$; +10%: $p < 0.001$; +15%: $p < 0.001$; +20%: $p < 0.001$). Negative ankle joint work was smaller in the +5% condition compared to the +15% ($p = 0.012$) and +20% conditions ($p < 0.001$). Further, negative ankle joint work was smaller in the +10% condition compared to the +20% condition ($p = 0.020$).

Table 2. Lower extremity negative joint works and total negative joint works during each weighted condition for stair descent (J).

Joint	BW	+5%	+10%	+15%	+20%
Ankle	29.7 ± 9.6	34.8 ± 8.0a	37.5 ± 11.1a	40.2 ± 9.5 a,b	42.4 ± 9.2a,b,c
Knee	90.5 ± 19.8	96.8 ± 20.5	96.8 ± 25.7	97.7 ± 18.8	101.9 ± 20.8a
Hip	1.97 ± 1.09	2.26 ± 1.0	2.24 ± 1.11	2.20 ± 1.35	2.27 ± 1.40
Total	122.4 ± 25.6	134.1 ± 25.1a	141.7 ± 38.2a	141.8 ± 26.3a	148.6 ± 28.4a,b

Values recorded as mean ± SD. The letter “a” signifies a significant interaction compared to body weight (BW) “b” signifies a significant interaction compared to +5%, and “c” signifies a significant interaction compared to +10%.

Negative knee joint work was not affected by the added mass ($p = 0.111$; $F = 2.0$; Figure 2B, Table 2), though a general upward trend was associated with increasing added mass. Similarly, hip joint negative work was not affected by the added mass ($p = 0.577$, $F = 0.6$), though a general upward trend was observed with increasing added mass (Figure 2C, Table 2).

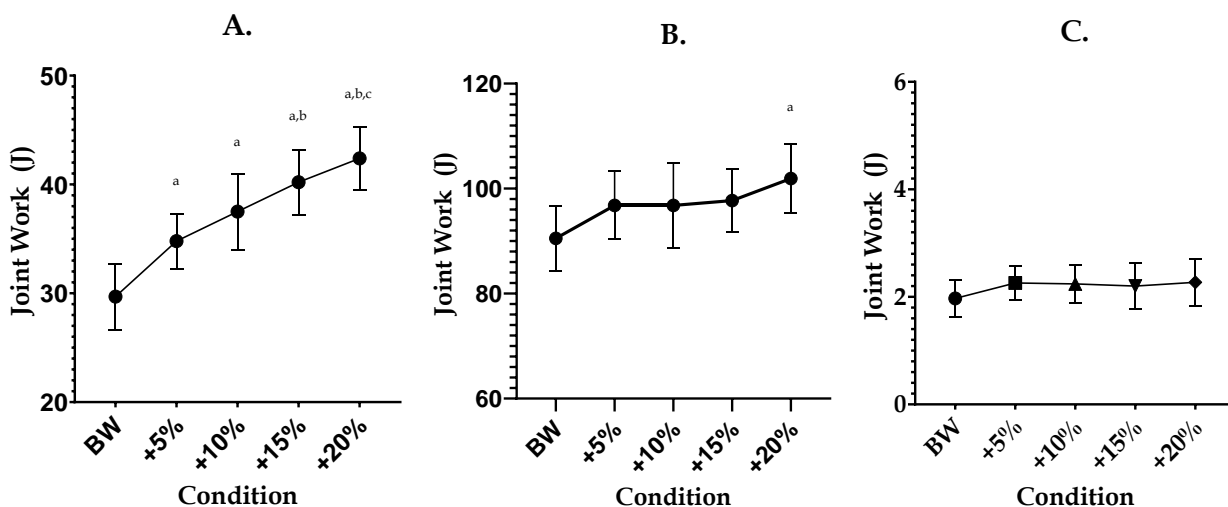


Figure 2. Absolute Negative A. Ankle, B. Knee, and C. Hip Joint Work values (J). The letter “a” signifies a significant interaction compared to body weight (BW), “b” signifies a significant interaction compared to +5% and “c” signifies a significant interaction compared to +10%.

Relative joint contributions to stair descent were defined as the percentage of total lower extremity negative work contributed by each joint. With increasing added mass was associated with greater relative contributions of the ankle to total negative lower extremity joint work ($p = 0.014$, $F = 3.7$; Table 3). Pairwise comparisons revealed that relative ankle contributions were greater in the +10% ($p = 0.043$), +15% ($p = 0.003$) and +20% ($p = 0.003$) conditions compared to the BW condition. No differences were present between the other loading conditions ($p > 0.05$). Relative joint contributions of the knee to total lower extremity work were reduced in response to increasing added mass ($p = 0.006$, $F = 4.3$; Table 3). Pairwise comparisons revealed no differences between the BW and +5% conditions ($p = 0.251$) though relative knee joint contributions were greater in the BW compared to +10% ($p = 0.003$), +15% ($p = 0.006$) and +20% ($p = 0.003$). Further, relative knee contributions were greater in the +5% condition compared to either the +10% ($p = 0.045$) and +20% conditions ($p = 0.048$). At the hip, relative joint contributions were not altered by the increasing mass added to the trunk ($p = 0.745$, $F = 0.488$; Table 3).

Table 3. Negative relative lower extremity work contributions (%).

Joint	BW	+5%	+10%	+15%	+20%
Ankle	24.3 ± 5.4	26.1 ± 4.3	27.1 ± 6.3a	28.6 ± 5.3a	28.7 ± 4.1a
Knee	74.0 ± 6.2	72.0 ± 4.5	68.5 ± 8.2a	69.0 ± 6.5a	68.6 ± 5.0a,b
Hip	1.6 ± 0.8	1.7 ± 0.7	1.7 ± 0.7	1.5 ± 0.8	1.5 ± 0.7

Values recorded as mean ± SD. Values recorded as mean ± SD. The letter "a" signifies a significant interaction compared to body weight (BW) and "b" signifies a significant interaction compared to +5%.

DISCUSSION

The purpose of this study was to investigate the influence of body mass on lower extremity joint work during a stair descent task. The major findings of this study were that increasing body mass was associated with greater total lower extremity joint work as a result of increases in ankle and knee joint work. Conversely, for relative joint contributions to lower extremity work, increasing body mass was associated with greater ankle joint contributions and reduced knee joint contributions. No changes in hip joint work or hip joint contributions to total lower extremity work were observed with increasing body mass.

Increasing mass was associated with greater lower extremity joint work values. Specifically, ankle and knee joint work values increased as a result of greater added mass resulting in greater total lower extremity work. Though limited data exists concerning the influence of body mass on lower extremity work during stair negotiation, ample evidence has been reported concerning the relationship between body mass (or added load) and lower extremity work during over ground walking. Research has shown that increasing backpack loads yield a linear increase in total lower extremity work suggesting that the healthy neuromuscular system is capable of accommodating task-specific increases in mechanical demand (16). However, obesity is not an acute condition but represents a chronic increase in body mass. Similar to acute added mass, obese adults exhibited greater total mechanical work than non-obese adults during an over ground walking task while the greater mechanical work in obese individuals was attributed to

their greater body mass (26). Several candidate mechanisms may underlie the observed increases in total lower extremity work associated with increasing mass. One potential mechanism is that the added mass required greater extensor moments at the ankle and the knee to control limb collapse during the stair descent task altering the peak joint power at the knee and hip underlying the joint work calculation. DeVita and Hortobagyi (2003) investigated the effect of obesity on lower extremity joint moments during locomotion and revealed that obese individuals perform locomotion tasks with greater peak ankle and knee extensor moments compared to non-obese individuals. DeVita and Hortobagyi's (2003) findings are supported by further research demonstrating that obese adults perform locomotion tasks with greater peak knee extensor moments than non-obese adults (4). The previously reported increases in ankle and knee joint moments associated with obesity mirrors the current joint-level findings of greater ankle and knee joint work with increasing added mass. An alternative mechanism may relate to joint angular velocities. Specifically, increases in joint angular velocities would influence the joint power calculation underlying the joint work calculation (21).

While joint work values demonstrate load-induced changes in joint mechanics during stair descent, relative joint contributions to total lower extremity work may provide greater insight into changing motor strategies. The current findings demonstrated increases in ankle joint contributions to total lower extremity work while knee joint contributions to total lower extremity work were reduced in response to increasing added mass. These findings support the hypothesis that ankle contributions to total lower extremity work would increase while knee joint contributions to total lower extremity work would decrease. These findings are aligned with previous research which demonstrated a proximal-to-distal shift in joint work in obese compared to healthy weighted adults (12). In an overground walking task, obese adults exhibited greater ankle joint moments and work values, and smaller knee joint moments and work values compared to non-obese adults (12). However, recent research has revealed that weight loss is associated with modifications in lower extremity kinetic profiles including joint moments and powers (28). Specifically, during an over ground walking task, ankle plantar flexion moment and power were lower at 18 months (weight loss) compared to baseline when weight loss was induced by diet. Further, knee extension moments were increased at 6- and 18-month follow up visit compared to baseline when weight loss was induced via exercise (28). Therefore, the current findings in which body mass was modified by mass added to the trunk display similar trends to previous research studies which investigated weight loss induced changes in lower extremity joint kinetics. These similarities in findings suggest that the current model is sufficient to investigate changes in neuromuscular and biomechanical aspects of locomotor strategies in response to weight loss.

While the current study reveals novel findings regarding mass-invoked biomechanical plasticity during stair descent, we acknowledge several limitations. One limitation of the current study is the small sample size. While the inclusion of ten participants represents a small sample size which may negatively impact the generalizability of these findings, an a priori power analysis suggested that 9 participants were sufficient to perform this study. As such, we believe the study had sufficient power to investigate the influence of body mass and added mass on lower

extremity joint work profiles during stair descent. A second limitation of the current study was participation selection. The individuals recruited to participate in this study were all healthy, young adults with no history of major lower extremity injury including OA. Therefore, the capacity for adaptation would be greater than typical OA patients regardless of skeletal degeneration. Further, velocity could have affected lower extremity work, however a post-hoc analysis showed that velocity did not change across experimental loading conditions. However, the current findings are supported by biomechanical changes observed in weight loss studies following 18 months of intervention, therefore, the differences in mechanical capacity between participants in the current study and obese individuals may not influence the generalizability of these findings. A third limitation pertains to the characteristics of the added mass. Specifically, the added mass was a rigid mass applied symmetrically to the torso while the fat mass associated with obesity is non-rigid in nature and is applied across the entirety of the skeleton. An important aspect of obesity-related mass that was not adequately simulated in the current study is the increased thigh girth associated with whole-body obesity. Research has demonstrated that changes in thigh girth alone can alter lower extremity biomechanics during an overground locomotion task (39).

Increasing mass is associated with increased lower extremity work at the ankle and knee as well as a proximal-to-distal redistribution of joint contributions from the knee, toward the ankle during a stair descent task. Interestingly, no changes in hip joint work or hip joint contributions to lower extremity work were observed. These findings suggest that acutely increased mass added to the trunk induces biomechanical plasticity in response to increased mechanical demand during stair descent. Future research should consider the influence of chronic changes in body mass on lower extremity work and joint contributions during stair ascent and descent tasks. Further, evaluation of joint loads and muscular contributions to load attenuation during stair descent should be considered.

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