Effects of Stride Length on Knee Loading in Simulated Obese Populations

By

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Abstract

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BACKGROUND: Walking is part of our daily activities. Increasing body mass potentially increases biomechanical mal-adaptations including reduced step length (SL), and increases joint loading (JRF). **PURPOSE:** The purpose was to determine if acutely added mass (AM) or SL change knee JRFs during walking. Hypotheses included: AM will alter SL, reduced SLs will increase JRFs, and AM increase JRFs. **METHODS**: Fourteen participants performed eight trials in four experimental conditions including two variations of SLs, and AM. 3D kinematics and ground reaction forces were collected simultaneously using an 8-camera motion capture system (240 Hz, Qualisys, Inc.) and force platforms (1200 Hz, AMTI, Inc.). Visual 3D was used to calculate joint angles, moments, powers and JRFs. **RESULTS:** Reduced SL had greater joint flexion angles, peak extension power, and JRFs than AM condition. **DISCUSSION:** It was concluded that reduced SLs are associated with greater JRFs while AM in isolation does not alter joint biomechanics.

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Introduction

According to the National Institute of Diabetes, 70% of the United States population is overweight or obese (1). Tennessee itself has the sixth highest rate of obesity in the nation. Further, Memphis has an obesity rate of 33.8% in 2015 (2, 3). These statistics reveal that Memphis is one of the most obese cities in America (4). From 1990 to 2015, the obesity rate in Tennessee has increased by 20% and continues to increase (2). As a nation, the prevalence of obesity is predicted to be 30-37% in men and 34-44% in women in adults by the year of 2020 (5). Increasing obesity rates result in secondary increases in cardiovascular and musculoskeletal disorders which results in a concomitant increase in healthcare cost for the individuals as well as the nation. As a nation, the United States averaged $26 billion dollars for medical costs of obesity-related health issues over the six-year period from 2005 to 2011. As an individual the annual cost of being obese is estimated to be between $2,741 and $3,613 more compared to healthy individuals each year (6). As a country, state and city, we collectively are negatively affected by obesity.

Obesity is a scale of excess weight that is associated with adverse effects to health (7). A widely accepted way to assess body morphology is through a body mass index (BMI). BMI, calculated as the quotient of an individual's body mass divided by their height (in meters) squared (8), is used to categorize individuals into underweight (< 18 kg/m^2), normal (18 kg/m^2 – 25 kg/m^2), overweight (25 kg/m^2 – 30 kg/m^2) or obese (>30 kg/m^2). A positive correlation exists between BMI and mortality rates with greater BMI associated with higher mortality rate (5). Further, it is suggested that even modest increases in body weight have negative effects on lifespan (Figure 1). It is suspected that the serious negative effects of increasing body weight are not solely due to higher BMI values but are the result of secondary effects of obesity including metabolic disorders, hyperlipidemia, hypertension, and diabetes (9).

Though obesity has deleterious effects on cardiovascular and metabolic health, obesity is also known to lead to chronic musculoskeletal conditions such as osteoarthritis (10, 11). Osteoarthritis (OA) is a progressive degenerative disorder of the articular cartilage around a joint, in this case, the knee. Out of the population in the United States (~330 M people), 27 million individuals have been diagnosed with OA, equating to more than 8% of the nation (12). OA accounts for an estimated $10 billion in healthcare costs each year (13). Mechanically, with every 5kg of weight gained, increases the risk of osteoarthritis by 36% (14). Though increasing body mass is associated with greater mechanical loading to the lower extremity, a number of related to biomechanical mal-adaptations that include reduced step length, greater step width and an increased knee joint load.

Obese populations demonstrate aberrant gait biomechanics. Specifically, obese individuals walk with shorter step lengths and greater step widths compared to healthy individuals. A shorter step length is suggested to direct the forces of the system in a vertical direction which may increase skeletal joint loading (15, 16). A larger step width leads to a decrease in peak knee joint moments and an increase in mediolateral ground reaction forces causing abnormal motion and loading in the knee joint, potentially increasing the risk of musculoskeletal insult and injury (17). These two factors in combination (increased load and greater skeletal involvement) may underlie the higher rates of osteoarthritis in obese individuals exacerbating a sedentary lifestyle and furthering their obesity.

Mechanically, obesity effects multiple aspects of daily living. To participate in ADLs, functional capacity has to be present with a low disability. Functional capacity for individuals overall decreases as BMI increases (5). Past research has also found a positive correlation between disability and obesity (18). Specifically, disability in this case will be defined by the increase in knee OA. The pathophysiologic process of knee OA has been identified biomechanically as an increase in knee-joint forces and knee-joint moments. Past research has examined this through changes in body mass (i.e. weight loss). Knee joint adduction moments have been related to an increase in compressive loads (19), and weight loss has been found to reduce significant compressive knee-joint loads, or forces (20). Overall, obesity affects movement of everyday life functionally and the ability of the individual to do daily tasks. Physical activity has been proven to help decrease BMI ratings, obesity, and even mortality rates (21). A daily task that is available and physically demanding to most individuals is walking. To increase physical activity, a successful treatment many physicians prescribe are to increase step goals for obese individuals. In order for a transition for obese individuals to increase physical activity per day, walking mechanics are important to examine to ensure that these individuals do not have secondary affects from an increase in walking prescription.

Though it is clear obesity results in altered gait biomechanics, the role of shorter step lengths on knee joint loading in obese individuals has not been established. Messier et al. (22) reported that each pound of weight lost results in a four-fold reduction in knee joint load per step during daily activities. It has also been suggested that decreases in weight in combination with increased stride lengths result in substantial reductions in knee joint loading (23). In contrast, Milner et al. (20) has suggested that a shorter stride length, would reduce the vertical impulse applied to the knee joint reducing the risk of developing OA. An important difference in these studies pertains to the population of interest. While Milner et al. (20) focused on obese individuals at a single point in time, DeVita et al. (23) performed an intervention study and evaluated gait biomechanics across multiple time points in a repeated measures design. The role of step length in knee joint loading has not been well established. A need exists to investigate the role step length and increasing body mass on knee joint loading during gait. Therefore, the purpose of this study was to (a) determine if acutely added mass (weight vest) results in changes in step length during walking, (b) to determine if reduced step lengths independently (in the absence of added mass) increases knee joint loading, and (c) to determine if added mass results in an increase in knee joint loading. It was hypothesized that: (a) acutely added mass will result in differences in step lengths, (b) reduced step lengths will result in an increase in joint loading, and (c) added mass will alter biomechanical variables and increase joint loading.

Methods

Participants

The location this experiment took part in was the Musculoskeletal Analysis Laboratory, School of Health Studies, University of Memphis, in Memphis, Tennessee. Participants visited the Musculoskeletal Analysis Laboratory (MAL) once for examination and testing. The session's duration lasted from 60 to 90 minutes. Prior to any warmup, measurements or testing, individuals screened for inclusion in this study, provided written informed consent and completed a verbal training history to determine study eligibility, and a written *Physical Activity Readiness Questionnaire* (PAR-Q; Appendix A). For each session, testing occurred in the following order: (1) warm-up exercises, (2) placement of measurement sensors, and (3) completion of walking trials including four experimental conditions involving the interaction of two step length conditions and two added mass conditions.

Experimental Equipment

Anthropometric measurements included: age, sex, height, and body mass. The following measurements were recorded using a stadiometer and scale. Following anthropometric measurements, retro-reflective markers were placed bilaterally on the participant's lower extremity including the trunk, pelvis, thigh, shank and feet to measure individual segment motion during walking trials (step length x added mass) using a 9-camera motion capture system (240 Hz, Qualisys AB, Goteburg, Sweden). A pair of force platforms were used to record ground reaction forces (GRFs; 1200 Hz, AMTI Inc., Watertown, MA, USA).

Overground Walking Procedure

All walking trials required the participants to perform eight over ground walking trials across a 20-meter walkway in each of the four experimental conditions. Experimental conditions include the interaction of two step lengths (natural and constrained, 0.68m) and two weighting conditions (unloaded and loaded) at the participants preferred walking speed. The self-selected walking velocity was characterized as the pace at which the participant would normally walk during daily activities. The natural step length condition allowed participants to walk with their chosen step lengths while the constrained step length condition required participants to walk with a step length of 0.68 m as outlined on the laboratory floor using masking tape. The unloaded weighted condition was characterized as the participant walking without added load added onto the participants body mass. The added mass condition was characterized by the participant performing the walking trial with an added load by adding 20% of the participant's body mass by weighted plates into a vest that was placed among the participants chest. To ensure each participant qualified as "obese" in the added mass conditions, a BMI calculation was performed with the added load to identify if each participant's new BMI exceeded 30 kg/m^2 to classify them in the obese category.

A successful walking trial was characterized by the participant walking across the runway at the prescribed velocity and having the foot of interest fully supported by the force platform in the center of the walkway. Participants completed eight successful walking trials per condition totaling 32 walking trials with 60- to 90-second periods of rest between trials to avoid fatigue. Participants wore their active shoe of choice to perform the movements.

Data Analysis

Data captured from the three-dimensional motion capture system were labeled and exported to c3d file. Visual 3D (C-Motion, Bethesda, MD, USA) was used to calculate knee joint angle, moment, and power time-series as well as the knee joint reaction force time-series. Custom software (Matlab, Mathworks, MA, USA) was used to calculate discrete biomechanical variables during the stance phase of gait including peak knee flexion, knee joint range of motion, peak knee extension moments and powers, and peak positive knee joint reaction force.

Statistics

Five 2 x 2 (load by step length) repeated measures analyses of variance was used to assess the interaction of mass and step length on biomechanical variables including: peak knee flexion angles, knee joint range of motion, peak knee extension moments, peak knee extension powers and peak knee joint reaction forces. In the presence of a significant interaction or significant main effect, post-hoc paired samples t-tests were used to determine the source of significance. Significance was set at $p < 0.05$.

Results

Table 1 presents the biomechanical variables of interest for each experimental condition including: peak knee flexion angle, knee joint range of motions, peak knee extension moments and powers and peak positive knee joint reaction forces. In Figure 1, no mass by step length interaction was observed for peak knee flexion angles ($p = 0.524$). The constrained step length was associated with greater peak knee flexion angles than the preferred step lengths ($p = 0.043$). Post-hoc t-tests revealed that peak knee flexion angles were greater in the constrained compared to preferred conditions for added mass ($p = 0.03$) not the unloaded condition ($p = 0.08$). No effect of mass was observed for peak knee flexion angles ($p = 0.578$). In contrast to peak knee flexion angles, no mass by step length interaction was observed for knee joint range of motion in Figure 2 ($p = 0.571$). Further, no main effect of step length ($p = 0.299$) or mass ($p = 0.585$) was observed for knee joint range of motion.

In Figure 3, no mass by step length interaction was observed for peak knee extension moment ($p= 0.306$). Further, no main effect of step length ($p = 0.153$) or mass ($p = 0.626$) was observed for peak knee extension moment. For peak knee extension power in Figure 4, no mass by step length interaction was observed ($p = 0.306$). However, a significant main effect of step length was observed ($p = 0.037$). Post-hoc t-tests revealed that peak knee extension power was greater in the constrained compared to preferred step length conditions in the added mass condition ($p = 0.007$) but not the unloaded condition ($p = 0.09$).

For knee joint reaction forces in Figure 5, no mass by step length interaction was observed ($p = 0.753$). A main effect of step length was observed ($p = 0.019$). Post-hoc analyses revealed greater knee joint reaction forces in the preferred compared to constrained step lengths in both unloaded ($p = 0.023$) and added mass conditions ($p = 0.048$). No main effect of mass on peak knee joint reaction forces was observed ($p = 0.918$).

Discussion

The purpose of this study was to determine if acutely added mass and/or step length change knee joint loading during level walking. The major findings of the current study demonstrate that acutely added mass does not alter knee biomechanics, however, constraining step length alters both knee joint kinematics and kinetics. Specifically, constrained step lengths were associated with greater peak knee flexion angles as well as greater joints powers and joint reaction forces.

Current data revealed that acutely added load does not alter knee joint moments and powers during walking. These findings are in contrast with previously published research that demonstrated with added load at the knee during walking tasks relative to mass of the individual: directly affected joint loads per step and reduced range of motion (20, 24). This difference in results can be explained as a chronic versus an acute response, as Messier et al.'s (22) study was performed in six sessions over an 18-month long weight loss intervention for obese adults. Rather, acute responses to added load have been noted in numerous other studies (24, 25). Potential reasons for the differences could be that the added load was not sufficient to create an acute response in recreational athletes. Knapik et al. (25) started to see significances at 50% of body weight and up added onto their trained military professionals for kinematic and kinetic differences in walking. This could indicate that a higher stimulus was needed to evoke a difference in our participant population.

However, step length was a strong enough stimulus to evoke a response in knee joint flexion, power, and joint reaction forces. Our findings are supported by Milner et al. (20) where they found that shorter stride lengths reduce knee adduction joint loading. Our results mirror their findings by greater knee joint loads in the preferred step length (i.e., longer step length) compared to the constrained condition in both the loaded and unloaded conditions however in different planes (frontal vs sagittal) in knee flexion, not adduction.

The mechanisms behind an increase in knee joint loading with a longer step length can be defined through kinematic and kinetic variables such as; peak knee flexion, extension power, and extension moments. For peak knee flexion, the constrained step length increased under added load compared to the preferred step length condition. Our interpretation is that with an increase in load the subject adapted to the load by increasing their muscular contribution by flexing the knee, therefore recruiting more muscles to attenuate load. However, this was not represented in the range of motion due to the un-altered state for the constrained added mass condition. This finding is contradicted by Attwells et al. (24), where they found that knee range of motion increases in conjunction to increased load, rather to the knee not changing as load increased. Since range of motion did not change, extension moments at the knee also did not change between conditions and an increase in flexion was observed, potentially our participants walked with their knee more bent, providing a more athletic stance without reaching full extension in between walking phases.

Since there was an increase in peak knee flexion making a more crouched position, an increase of peak knee extension power was potentially due to the increase in force the muscles had to produce while maintaining this flexed position while walking. With the same distance, and time the participant had to make a step, the increase in muscle force is a potential source to the increase in peak knee extension power. While our findings suggest that an increase in muscular contribution to attenuate load helps preserve knee health, past research also states that with an increase of load leads to an increase in muscular tension and knee injury (24).

There are numerous limitations to the following study, the location of the added load was a contributor to our research boundaries. In this study, the added mass was added to the chest. In obese individuals, accumulative load is seen in alternative areas such as the thigh and lower abdominal regions. This could potentially alter kinematic variables in walking. As shown by Westlake et al. an increase in thigh circumference alters walking kinematics (16). Potentially if the load was distributed in other regions, such as the thigh, with altered kinematics we could potentially alter walking kinetics. One limitation could be that all of our subjects were athletes and not obese individuals. This could affect our results for that the individuals who participated were recreationally active and have an increased ability to adapt to stress unlike the population that this study simulated, obese adults. This was seen by Knapik et al. (25), where they found that foot soldiers did not have altered walking biomechanics until over fifty percent of their body weight was added to their weighted vest. Future studies should look at added load in alternate locations and with different populations to note if a simulated state shows accurate similarity between the two.

The current data demonstrate that increased step length, with or without added mass, decreases the load on the knee. Our findings add to past research that find an increase in stride length could help decrease the risk to skeletal structures by increasing the contributions to muscular components. This information can be applied clinically to individuals with a high risk of OA such as older and obese populations to make conscious decisions to increase stride length.

However, more studies are needed to investigate simulated obese states to ensure a correlation between ‘obese’ and ‘simulated’ investigation data collection structures.

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Figure Captions

Figure 1. Peak knee flexion (deg) during level walking with increased mass and constrained step lengths. Constrained step length was associated with significant increases in peak knee flexion angles ($p = 0.040$). No changes were observed for added mass ($p = 0.520$).

Figure 2. Peak knee range of motion (deg) during level walking with increased mass and constrained step lengths. No changes were observed for added mass ($p = 0.57$) or constrained step length ($p = 0.30$).

Figure 3. Peak Knee Extension Moment (Nm/kg) during level walking with increased mass and constrained step lengths. No changes were observed for added mass ($p = 0.31$) or constrained step length ($p = 0.15$).

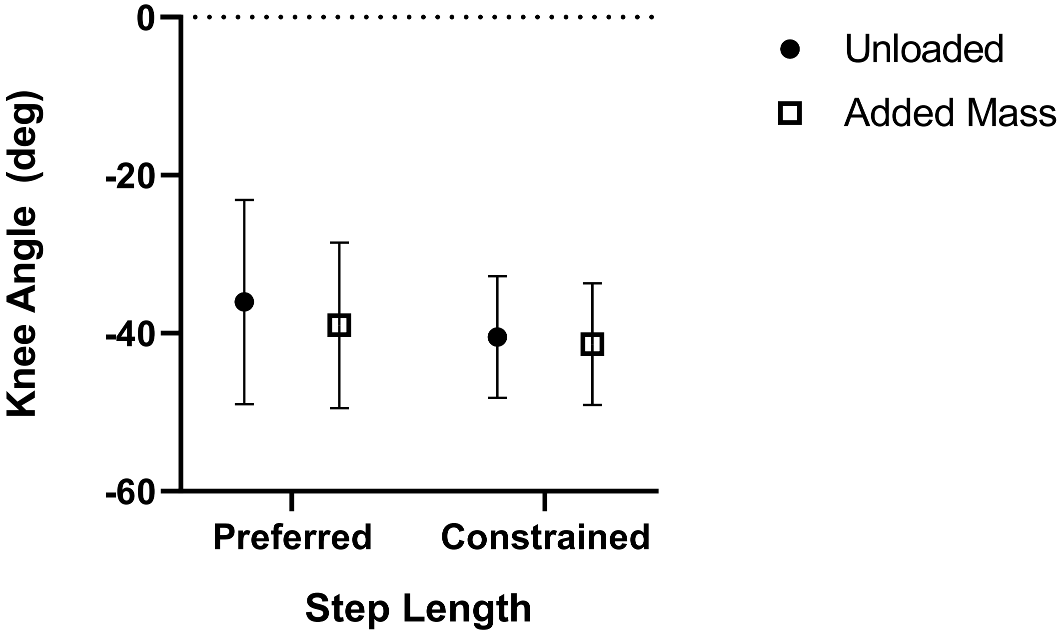
Figure 4. Peak Knee Extension Power (W/kg) during level walking with increased mass and constrained step lengths. Constrained step length was associated with significant increase in peak knee extension power ($p = 0.04$). No changes were observed for added mass ($p = 0.61$).

Figure 5. Peak Vertical Joint Reaction Forces (N/kg) during level walking with increased mass and constrained step lengths. Constrained step length was associated with greater knee joint reaction forces ($p = 0.02$). No changes were observed for added mass ($p = 0.75$).

Table 1. Mean peak flexion angles, ranges of motion, peak knee extension moments and powers and joint reaction forces during level walking in each of four experimental conditions. Data are presented as mean ± SD. Statistical findings are presented by the omnibus p-value.

Variable	Body Mass			Added Mass		
	Preferred SL	Constrained SL	p-value	Preferred SL	Constrained SL	p-value
Peak Knee Flexion Angle (deg)	-36.0±12.9	-40.5±7.7	0.04	39.0±10.5	-41.4±7.7	0.52
Range of Motion (deg)	40.4±13.2	43.3±6.8	0.30	43.1±10.1	43.9±4.8	0.57
Peak Knee Extension Moment (Nm/kg)	2.9±2.3	2.3±0.8	0.15	2.4±0.7	2.3±0.9	0.31
Peak Knee Extension Power (W/kg)	6.1±4.2	4.6±1.0	0.04	5.7±1.8	4.8±1.0	0.61
Knee Joint Reaction Forces (N/kg)	7.1±2.0	6.1±1.1	0.02	6.9±2.3	5.4±3.1	0.75

Figure 1.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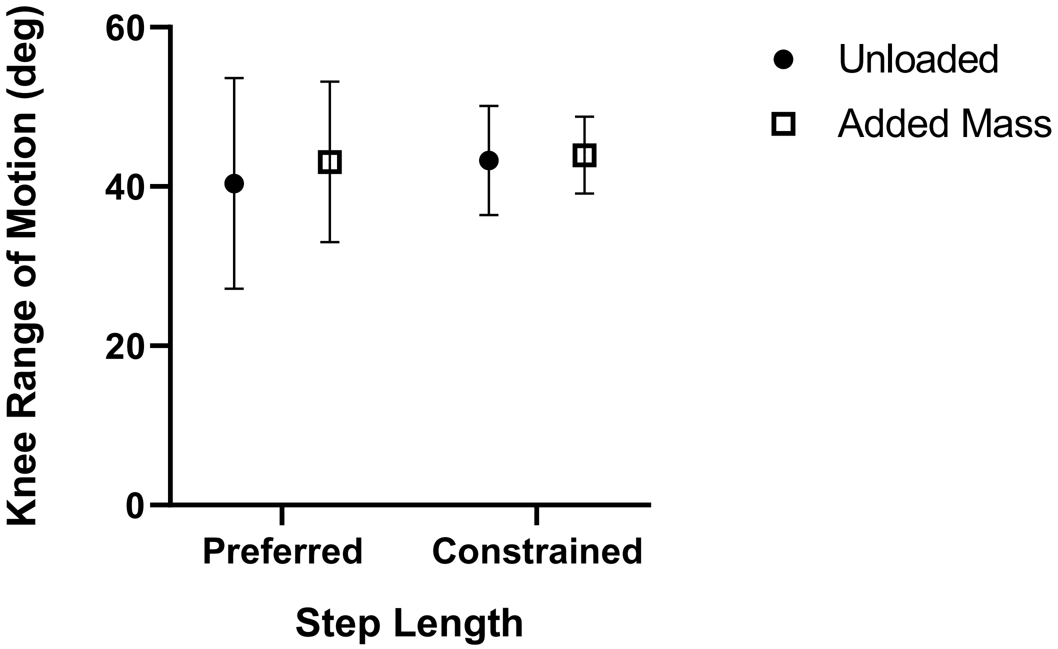
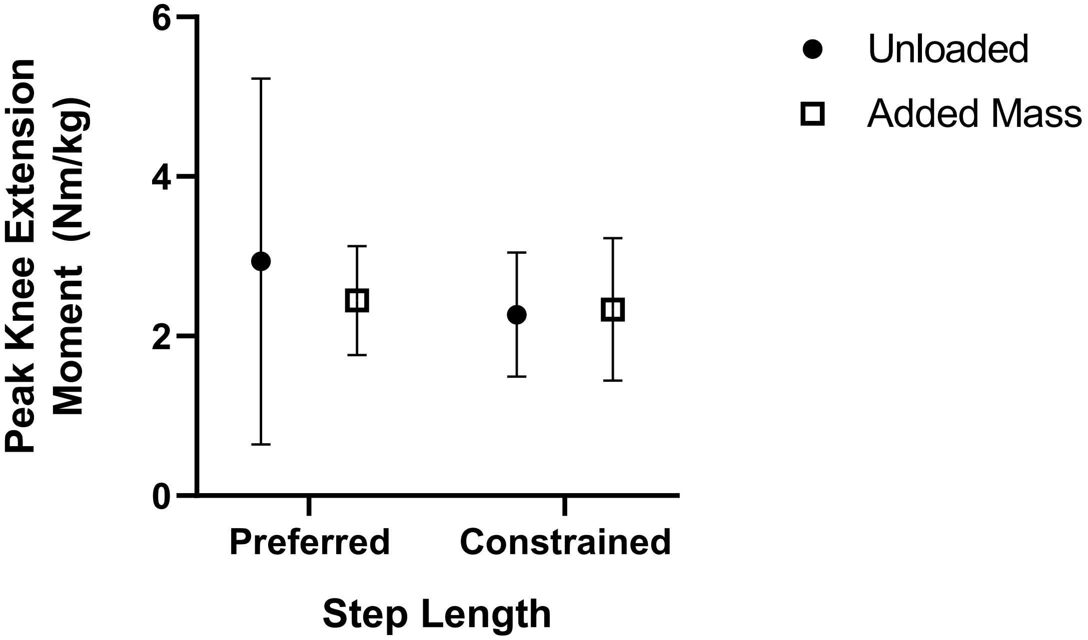
-20
-40
-60
Knee Angle (deg)
Preferred
Constrained
Step Length
● Unloaded
□ Added Mass

Figure 2.



Knee Range of Motion (deg)
60
40
20
0
Preferred
Constrained
Step Length
● Unloaded
□ Added Mass

Figure 3.



Peak Knee Extension Moment (Nm/kg)
6
4
2
0
Preferred
Constrained
Step Length
● Unloaded
□ Added Mass

Figure 4.

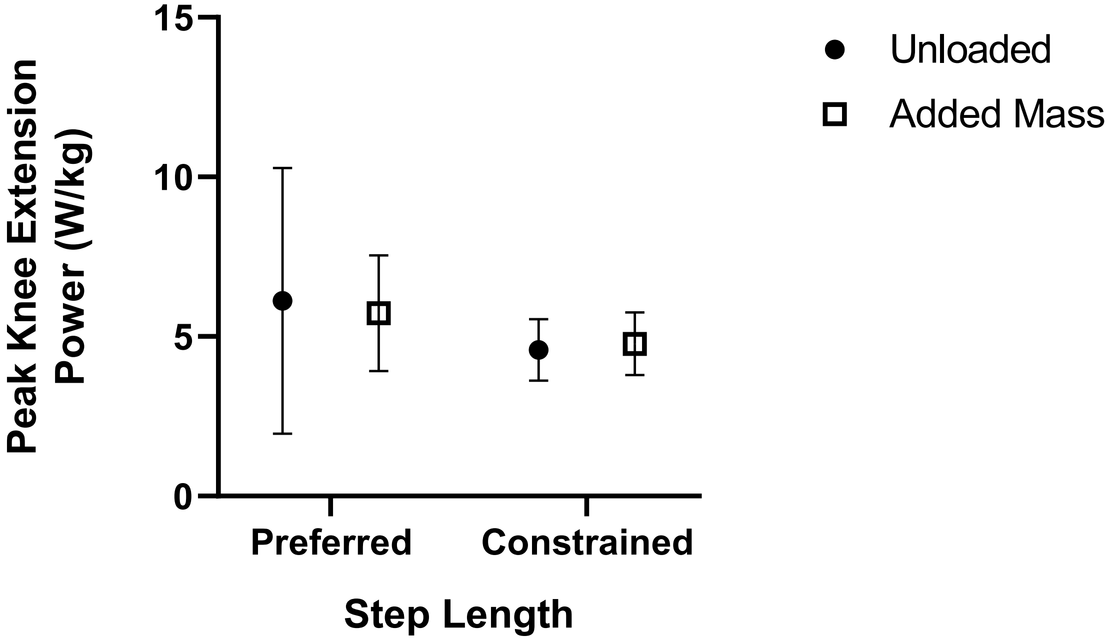
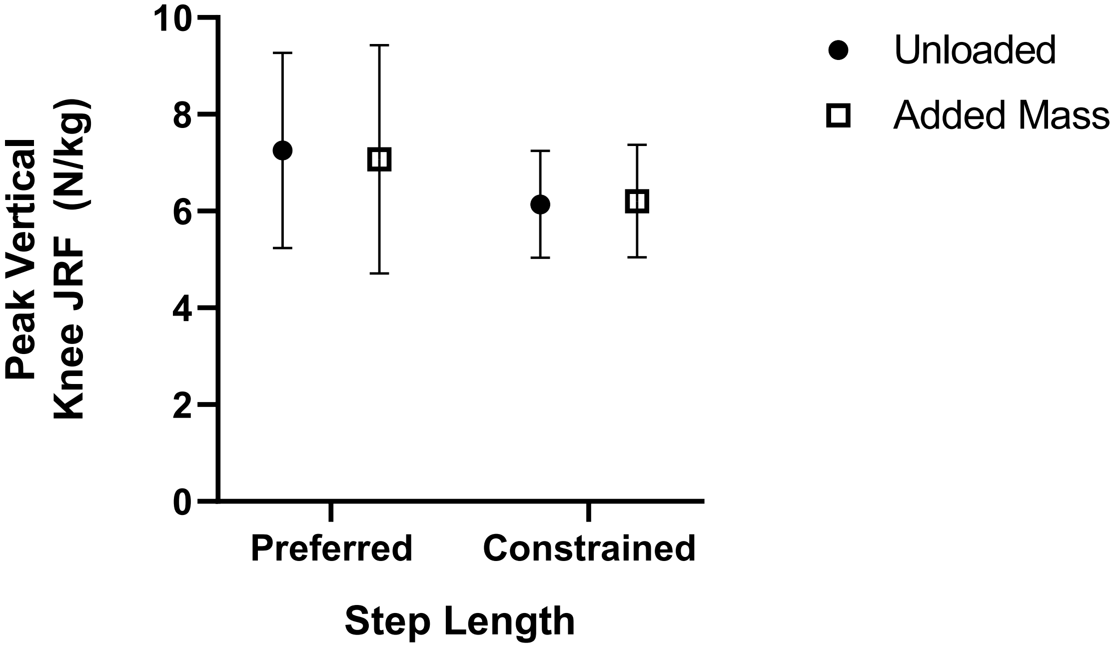

15
10
5
0
Peak Knee Extension Power (W/kg)
Preferred
Constrained
Step Length
● Unloaded
□ Added Mass

Figure 5.



10
8
6
4
2
0
Peak Vertical Knee JRF (N/kg)
Preferred
Constrained
Step Length
● Unloaded
☐ Added Mass