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Carrying asymmetric loads during stair negotiation

Junsig Wang
Iowa State University

Jason C. Gillette
Iowa State University, gillette@iastate.edu

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Keywords
Gait, Asymmetric load, Load carriage, L5S1, Low back, Joint moment

Disciplines
Applied Mathematics | Control Theory | Kinesiology | Motor Control | Musculoskeletal System

Comments
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CARRYING ASYMMETRIC LOADS DURING STAIR NEGOTIATION

Abstract

Individuals often carry items in one hand instead of both hands during activities of daily living. The combined effects of carrying asymmetric loads and stair negotiation may create even higher demands on the low back and lower extremity. The purpose of this study was to investigate the effect of symmetric and asymmetric loading conditions on L5/S1 and lower extremity moments during stair negotiation. Twenty-two college students peformed stair ascent and stair descent on a three-step staircase (step height 18.5 cm, tread depth 29.5 cm) at preferred pace under five load conditions: no load, 10% body weight (BW) unilateral load, 20% BW unilateral load, 10% BW bilateral load, and 20% BW bilateral load. Video cameras and force platforms were used to collect kinematic and kinetic data. Inverse dynamics was used to calculate frontal plane moments for the L5/S1 and lower extremity. A 20% BW unilateral load resulted in significantly higher peak L5/S1 lateral bending, hip abduction, and external knee varus moments than nearly all other loading conditions during stair ascent and stair descent. Therefore, we suggest potential benefits when carrying symmetrical loads as compared to an asymmetric load in order to decrease the frontal joint moments, particularly at 20% BW load.

Word count: 2970

Introduction

Individuals often carry items in one hand instead of both hands during activities of daily living such as walking and stair negotiation. Holding an object with one hand is frequently utilized when the carried object has a handle or to allow the opposite hand to be free for other activities. Previous studies have shown that level walking while carrying asymmetric loads with one strap backpacks or mailbags resulted in higher trunk lateral bending [1, 2], higher trunk forward lean [2], and higher levels of perceived low back pain [3] than unloaded walking. In addition, studies have shown that walking while carrying asymmetric loads in a bag or sidepack resulted in higher hip abduction moments [4, 5] and higher L5/S1 bending moments [5] than unloaded walking. These studies provide evidence that asymmetric load carriage during walking increases frontal plane loading in both the low back and lower extremity. Therefore, it is important that further research is conducted to investigate the effect of asymmetric load carriage on the low back and lower extremity in an effort to reduce the potential for injury.

Stair negotiation is an activity of daily living that commonly involves load carriage. Previous studies have reported that unloaded stair ascent and descent required higher ankle dorsiflexion angles [6], knee flexion angles [6, 7], and knee extension moments [6, 7] as compared to level walking. Hall et al. (2013) found that carrying symmetric loads of 13.6 kg (approximately 20% body weight) in a container in front of the body or in a backpack resulted in higher external knee varus moments than when carrying no load [8]. Furthermore, stair ascent resulted in higher external knee varus moments than walking or stair descent across loading conditions. These findings indicate that stair negotiation involves higher knee extension moments than walking [6, 7] and that load carriage during stair ascent may also result in higher external knee varus moments [6-8].

The effects of asymmetrical load carriage during stair negotiation remain largely unknown, as previous asymmetrical load carriage studies have primarily focused on level walking or lifting tasks. Hong and Li (2005) found that carrying asymmetric loads in a one-strap athletic bag resulted in higher normalized vertical ground reaction forces at 10% of body weight for stair ascent and at 15% of body weight for stair descent as compared to no load [9]. These results indicate that load amount likely plays an important role in asymmetric load carriage during stair negotiation. However, few studies have been done to investigate adaptive joint mechanisms in the lower extremity and low back when carrying asymmetric loads during stair negotiation. Thus, there is a need for additional joint moment data that may provide insight for potential risk and development of lower extremity injuries and low back disorders.

This purpose of this study was to assess low back and lower extremity moments when carrying symmetric loads and asymmetric loads at several load amounts during stair ascent and stair descent. We hypothesized that 1) peak L5/S1 lateral bending moments would be significantly higher during unilateral load carriage when compared to bilateral load carriage and 2) peak hip abduction and external knee varus moments would be significantly higher during unilateral load carriage when compared to bilateral load carriage. Increases of these parameters may be associated with potential concerns of intervertebral disc strain and/or degeneration [10] and development of knee and hip osteoarthritis [11, 12].

Methods

Twenty-two healthy young adults with an age range of 20 to 36 (11 males and 11 females; age 24.2±4.3 years; height 170.8±7.7 cm; mass 67.8±13.8 kg) participated in this study. Participants were free of any pathology that would prevent them from being able to carry a 20% body weight load. Individuals were excluded if they had back, neck, leg, foot, or arm pain. Prior to participating in the study, each subject read and signed an informed consent form approved by the university's institutional review board.

Five load conditions were tested: no load, 10% body weight (BW) bilateral load, 20% BW bilateral load, 10% BW unilateral load, and 20% BW unilateral load (Figure 1). Loads were evenly split between the right and left hands during the bilateral load conditions. Hand-held bags were filled with sealed bags of lead shot to match the four loaded conditions. The unilateral load was carried in the participant's dominant hand. Since all participants were right-handed, they carried the hand-held bag in the right hand during the unilateral load condition. The weight carried in the bags was normalized according to each subject's body weight. These normalized loads were based on previous studies that indicated significant kinematic and/or kinetic changes when carrying loads ranging from 10% to 20% BW [2, 5, 8, 13]. Participants were instructed to ascend and descend a three-step staircase (step height 18.5 cm, tread depth 29.5 cm) at a preferred pace for each condition. The order of the conditions was randomized, and each condition was repeated three times. Participants were instructed to initiate stair negotiation by using the left leg on the first step and then the right leg on the second step.

A motion analysis system with 8 high-resolution cameras (Vicon Nexus, Los Angeles, CA) was used to collect three-dimensional kinematic data during each testing condition. The dynamic marker set included bilateral great toe, lateral mid-foot, lateral malleolus, anterior calf, lateral calf, lateral knee joint line, anterior thigh, lateral thigh, greater trochanter, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), and acromion process markers. Single sacrum and cervical markers were also included. Six additional markers (bilateral heel, medial malleolus, and medial knee joint line markers) were recreated using transformations determined from a static standing trial. Portable force platforms (AMTI, Watertown, MA) on steps one and two were used to collect ground reaction force data.

Data Processing

Kinematic data were captured at 160 Hz, and noise was reduced with a fourth-order, low-pass Butterworth filter at a cutoff frequency of 6 Hz. A static trial was used to estimate joint center locations which were assumed to be stationary in the segmental coordinate systems. Kinetic data were sampled at 1600 Hz and filtered at a cutoff frequency of 6 Hz. The force data were downsampled so that kinetic and kinematic data both had corresponding data points. Segment masses, center of mass locations, and moments of inertia were obtained according to De Leva's anthropometric model [14]. L5/S1 lateral bending moments and lower extremity (ankle, knee, and hip) frontal plane joint moments were calculated using inverse dynamics and rigid body assumptions. The location of the L5/S1 joint center was defined by creating a virtual point 34% of the distance from the sacrum marker to the midpoint of the ASIS markers [15, 16].

L5/S1 lateral bending moments were analyzed during single limb stance of the first and second stair steps. In order to calculate L5/S1 lateral bending moments during double limb stance, both left and right hip kinetics would be required. However, the hip kinetics for the lead and trial leg were not available at the top of the staircase (the third stair) because of the limited number of the force plates. Thus, single limb stance was utilized for L5/S1 lateral bending moments because the lead and trial legs were not always positioned on force platforms during double limb stance. Hip and knee frontal plane moments were analyzed during the entire stance phase of the first (left leg) and second (right leg) stair steps. Joint moments were transformed to the inferior segment coordinate axes and reported as an internal joint moments with the exception of knee varus moments, which were reported as external joint moments. Peak joint moments were determined across two steps and normalized by body mass. Absolute values of peak L5/S1 lateral bending moments were analyzed to avoid cancellation of left and right bending moments. All calculations were performed using a custom Matlab code.

Statistical analyses were performed using the SPSS statistical package (version 21; SPSS Inc., Chicago, IL, USA). The effect of the different loading conditions on peak joint moments was analyzed by using repeated measures Analyses of Variance (ANOVA). A one factor ANOVA design was used, and there were 5 levels of conditions (5 load conditions). When significant main effects were found, Bonferroni post-hoc tests were performed. The level of statistical significance for all tests was set at $p < 0.05$. To test the hypotheses, pairwise comparisons included differences between the five loading conditions.

Results

Peak L5/S1 lateral bending moments

There were significant differences in peak L5/S1 lateral bending moments as a function of load condition (Table 1). L5/S1 lateral bending moments were higher when comparing a 20% BW unilateral load to all other loading conditions during stair ascent and descent ($p < 0.001$). In addition, L5/S1 lateral bending moments were higher when comparing a 10% BW unilateral load to no load during stair ascent and descent ($p \leq 0.031$). Ensemble curves of L5/S1 bending moments are displayed in Figure 2.

Peak lower extremity frontal plane moments

There were significant differences in peak hip abduction moments as a function of load condition (Table 1). Hip abduction moments were higher when comparing a 20% BW unilateral load to all other loading conditions during stair ascent and descent ($p < 0.001$). In addition, hip abduction moments were higher when comparing a 20% BW bilateral load to no load and a 10% BW unilateral load during stair ascent ($p < 0.001$). Hip abduction moments were also higher when comparing a 10% BW unilateral load to no load and a 10% BW bilateral load during descent ($p \leq 0.001$), when comparing a 20% BW bilateral load to no load during stair descent (*p*

< 0.001), and when comparing a 10% BW bilateral load to no load during stair ascent and descent ($p \leq 0.022$). Ensemble curves of hip abduction moments are displayed in Figure 3.

There were significant differences in peak external knee varus moments as a function of load condition (Table 1). Knee varus moments were higher when comparing a 20% BW unilateral load to all other loading conditions during stair ascent and descent ($p < 0.001$). In addition, knee varus moments were higher when comparing 20% BW bilateral and 10% BW unilateral loads to no load and a 10% BW bilateral load during stair ascent and descent ($p \leq 0.001$). Knee varus moments were also higher when comparing a 10% BW bilateral load to no load during stair ascent ($p = 0.009$). Ensemble curves of external knee varus moments are displayed in Figure 4.

Discussion

The purpose of this study was to investigate the effects of carrying asymmetric loads on low back and lower extremity frontal plane moments during stair negotiation. Peak L5/S1 lateral bending, hip abduction, and external knee varus moments were significantly dependent upon load condition. Changes in low back and lower extremity frontal plane moments when carrying asymmetric loads during stair negation may provide important preliminary knowledge concerning potential risk of injury.

L5/S1 lateral bending moments

The first hypothesis that peak L5/S1 lateral bending moments would be significantly higher when carrying unilateral compared to bilateral loads was partially supported. L5/S1 lateral bending moments were higher when comparing 20% BW unilateral to 20% BW bilateral loads during stair ascent and descent, but there were no differences when comparing 10% BW unilateral and bilateral loads (Table 1). Similarly, Gillette *et al.* (2009) reported higher L5/S1 lateral bending moments when comparing 20% BW unilateral to 20% BW bilateral loads during walking in children [16]. Devita *et al.* (1991) also reported higher L5/S1 lateral bending moments when comparing a 20% BW asymmetric load to no load during walking [5]. Thus, it appears that a 20% BW load is at or beyond a critical level where asymmetry results in a substantial increase in low back moments for both walking and stair negotiation.

It should be stressed that peak L5/S1 lateral bending moments were dramatically increased when carrying a 20% BW unilateral load during both stair ascent and descent. During stair ascent, L5/S1 lateral bending moments for a 20% BW unilateral load were 72% higher than no load and 54% higher than a 20% BW bilateral load (Table 1, Figure 2). Furthermore, during stair descent, L5/S1 lateral bending moments for a 20% BW unilateral load were 75% higher than no load and 50% higher than a 20% BW bilateral load. These large increases in L5/S1 lateral bending moments may indicate an increased risk of low back injury. Increased L5/S1 lateral bending moments are linked to increased compressive spinal loading, lateral shear loading, and trunk muscle co-contraction [17]. A finite element study demonstrated that lateral bending moments resulted in shear strains in the annulus fibrosus [10]. Further, lateral bending moments combined with axial rotation moments can lead to rupture in the disc fibers [10]. Thus, greater than 20% BW asymmetric load carriage may result in substantial low back loading and be potentially injurious.

Another interesting finding was that the L5/S1 lateral bending moments for a 20% BW unilateral load were directed toward the left side of the body (Figure 2). A left lateral bending moment was toward the opposite side of the body (contralateral bending) where the unilateral load was carried. Furthermore, peak L5/S1 lateral bending moments for a 20% BW unilateral load occurred during step two of stair ascent and descent. Participants contacted step two with their right leg, which is the same side as the carried load during the unilateral conditions. Thus, it appears that the lower back is exposed to the highest lateral bending moments when the leg on the loaded side is performing a step during unilateral load carriage on stairs. However, further tests that alternate the lead leg or use a staircase with more steps are needed to rule out potential differences in loading between steps one and two.

Lower extremity frontal plane moments

The second hypothesis that hip abduction and external knee varus moments would be higher when comparing unilateral to bilateral load carriage was partially supported. Hip abduction and knee varus moments were higher when comparing 20% BW unilateral to bilateral loads during stair ascent and descent. Knee varus moments were also higher when comparing 20% BW unilateral to bilateral loads during stair ascent and descent, but hip abduction moments were only higher during stair descent (Table 1). As with the low back, it appears that a 20% BW load is at or beyond a critical level where asymmetry results in increases for hip and knee moments. Previous studies reported increased hip abduction and knee varus moments when carrying bilateral loads during walking and stair negotiation [8, 13]. Our findings demonstrate that increases in hip abduction and knee varus moments during stair negotiation are further amplified with asymmetrical loads.

Increases in external knee varus moments have been associated with development of chronic knee pain and asymptomatic medial knee osteoarthritis [18]. Higher knee varus moments may increase compression of the medial knee joint compartment during gait and may be associated with knee osteoarthritis development [11]. For example, a five year follow-up study indicated that higher knee varus moments resulted in thinning cartilage of the knee joint [19]. In addition, higher hip abduction moments may be related to changes in cartilage and greater incidence of hip osteoarthritis [12]. As the increases in knee varus and hip abduction moments were observed during only two steps, it remains to be seen if repetitive cycles of carrying a 20% BW unilateral load may result in higher risk of knee and hip joint injury and cumulative cartilage damage.

When carrying unilateral loads, peak hip abduction and external knee varus moments occurred during step one of stair ascent and descent (Figures 3, 4). Participants contacted step one with their left leg, which is the side opposite of where the unilateral load was carried. This finding may be explained by a larger frontal moment arm from the load in the right hand to the center of pressure under the left foot [20]. Similarly, DeVita *et al.* (1991) found higher hip abduction and knee varus moments in the leg opposite the load during walking with a sidepack [5]. Thus, it appears that the knee and hip are exposed to the highest frontal plane moments in the leg opposite the load during unilateral load carriage on stairs. As previously mentioned, additional tests alternating lead legs are needed to account for possible differences between step one and two.

There are several limitations of the current study. One of the limitations is that only two steps of stair negotiation were examined and double limb support was not included in the L5/S1 lateral bending moment. Another limitation is the potentially factors of step (step1 vs. step2) and limb (unloaded limb vs. loaded limb) that may influence the frontal joint moments. For instance, the initial step of stair negotiation can be considered a ‘transition step’ where mechanical demand increases [21]. Also, when carrying an asymmetric load, the frontal joint moments may be sensitive to the individual limb stance because of different moment arms from the center of pressure to the joint centers. Therefore, a further study should focus on these effects by testing both lead legs for each condition.

In summary, there were significant differences in low back and lower extremity moments when comparing load conditions. The 20% BW unilateral load resulted in higher L5/S1 lateral bending, hip abduction, and external knee varus moments than nearly all other loading conditions during stair ascent and descent. Therefore, we suggest potential benefits when carrying symmetric loads in order to decrease the frontal plane joint moments, particularly at the level of 20% BW loads.

Keywords : Gait, Asymmetric load, Load carriage, L5S1, Low back, Joint moment

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Table 1. Peak joint moments (mean ± standard deviation) as a function of loading condition during stair ascent and stair descent.

			Stair Ascent		
Joint Moment (N/kg)	No load	10% BW bilateral	10% BW unilateral	20% BW bilateral	20% BW unilateral
L5/S1 Lateral Bending	0.43±0.11	0.46±0.11	0.51±0.15	0.48±0.14	0.74±0.15[abcd]
Hip Abduction	0.98±0.14	1.07±0.19	0.99±0.15	1.12±0.17[ac]	1.33±.20[abcd]
External Knee Varus	0.57±0.18	0.62±0.19[a]	0.73±0.19[ab]	0.67±0.19[ab]	0.97±.24[abcd]
Ankle Eversion	0.09±0.06	0.10±0.11	0.11±0.07	0.10±0.06	0.12±0.06
Ankle Inversion	0.14±0.05	0.14±0.06	0.14±0.06	0.17±0.06	0.17±0.07
			Stair Descent		
Joint Moment (N/kg)	No load	10% BW bilateral	10% BW unilateral	20% BW bilateral	20% BW unilateral
L5/S1 Lateral Bending	0.55±0.19	0.61±0.25	0.74±0.20[a]*	0.64±0.25	0.96±0.21[abcd]*
Hip Abduction	1.12±0.17	1.24±0.15	1.36±0.16[ab]*	1.31±0.17[a]*	1.62±0.18[abcd]*
External Knee Varus	0.74±0.15*	0.77±0.16*	0.86±0.13[ab]*	0.87±0.15[ab]*	1.01±0.14[abcd]
Ankle Eversion	0.19±0.05*	0.20±0.05*	0.21±0.05*	0.22±0.05*	0.22±0.04*
Ankle Inversion	0.15±0.04	0.18±0.05	0.19±0.05[a]	0.20±0.06[a]	0.21±0.07[a]

[a] $p < 0.05$ vs. no load, [b] $p < 0.05$ vs. 10% BW bilateral, [c] $p < 0.05$ vs. 10% BW unilateral, [d] $p<0.05$ vs. 20% bilateral

* $p < 0.05$ ascent vs. descent

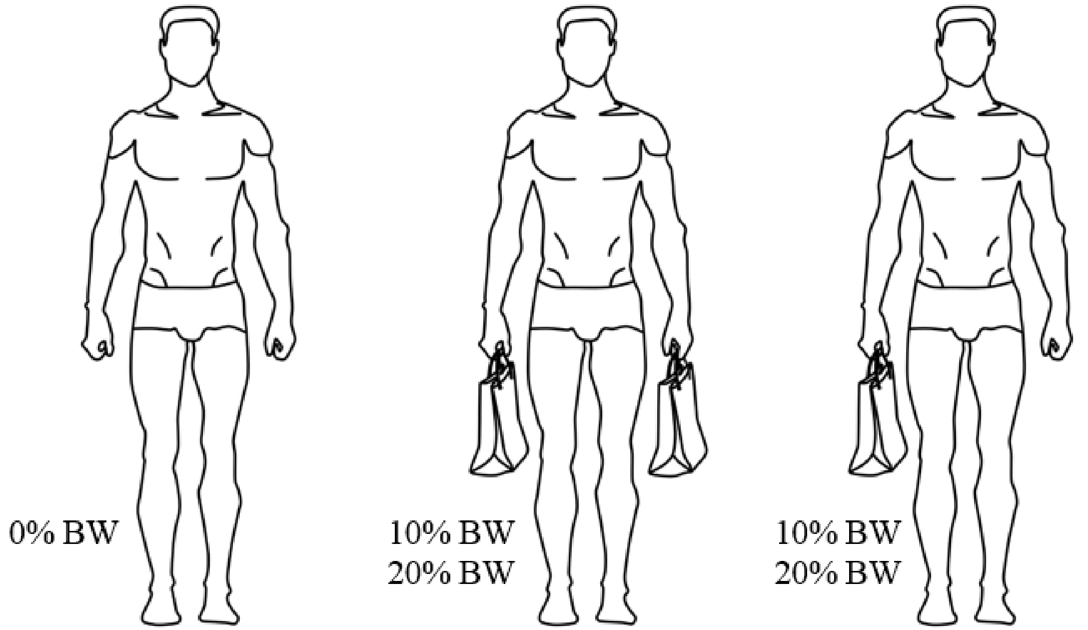

Figure 1. Illustration of the five load conditions. No load (left), 10% body weight (BW) bilateral load (center), 20% BW bilateral load (center),10% BW unilateral load (right), and 20% BW unilateral load (right).

Step one **Step two**

Left leg **Right leg**

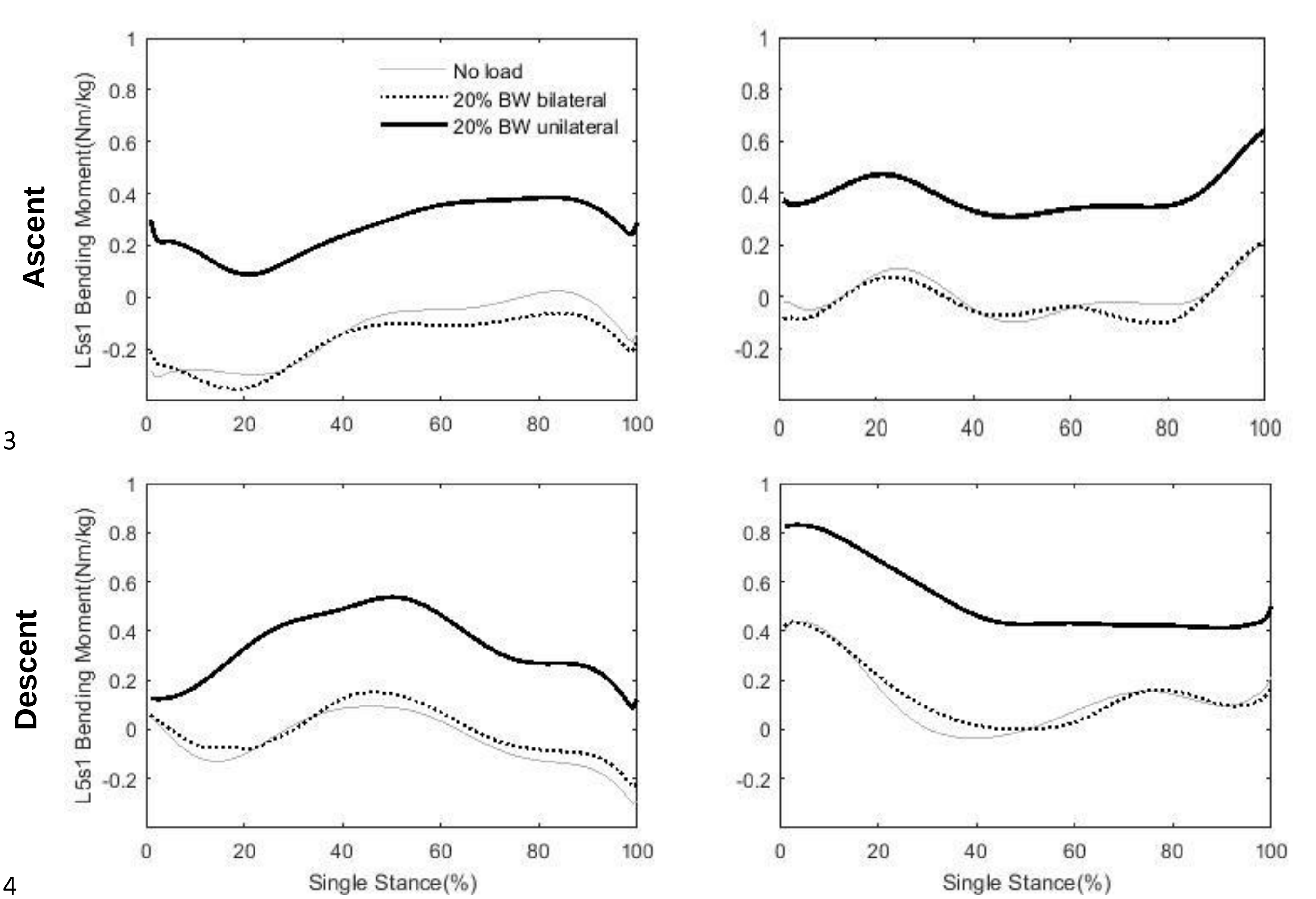

Figure 2. Ensemble curves for L5/S1 lateral bending moments during step one and step two of stair ascent and stair descent. Positive values indicate left bending moments, and negative values indicate right bending moments. Unilateral loads were carried in the right hand. For unilateral load conditions, positive values indicate contralateral bending moments, and negative values indicate ipsilateral bending moments.

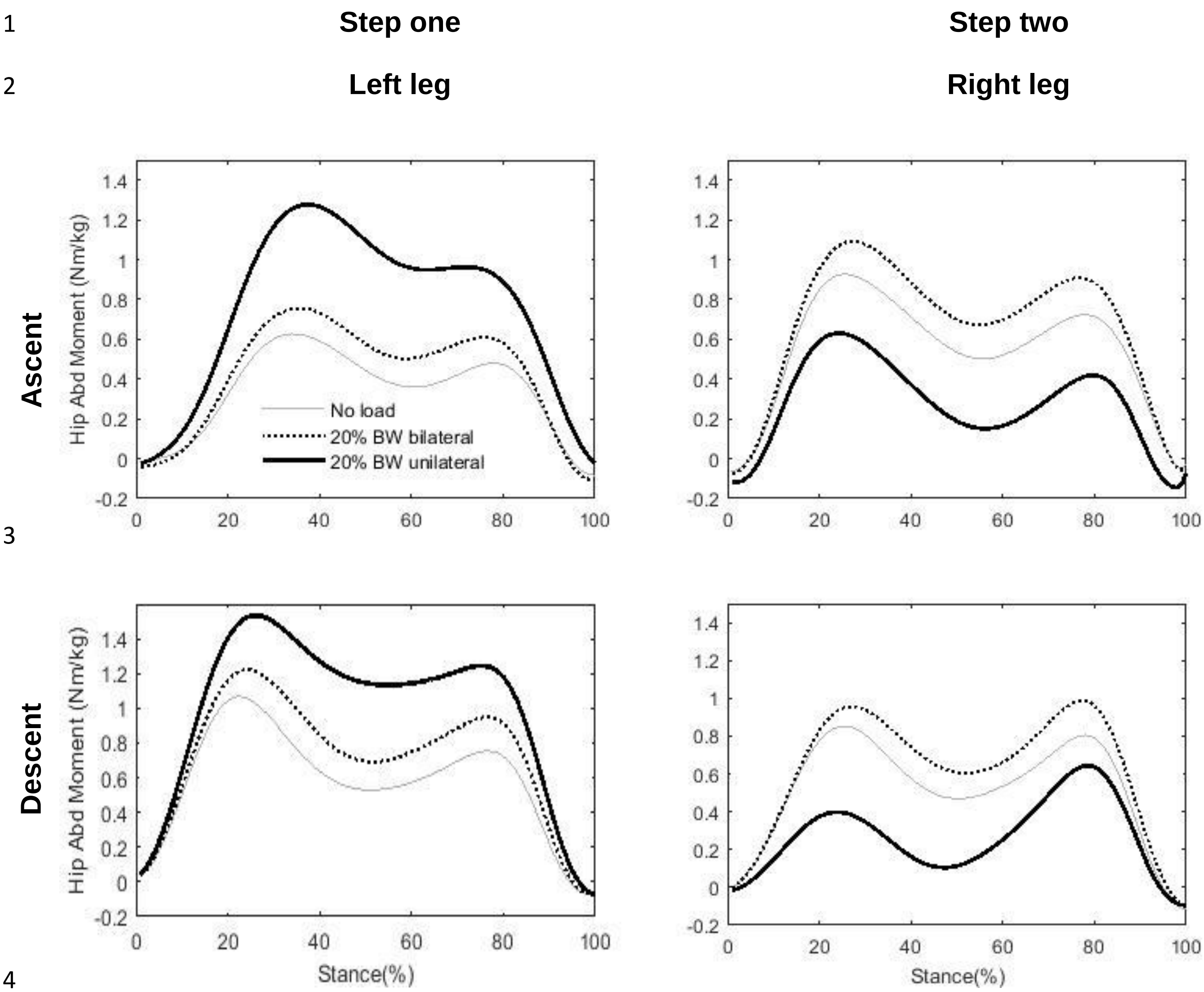

Figure 3. Ensemble curves for hip abduction moments during step one and step two of stair ascent and stair descent. Positive values indicate hip abduction moments, and negative values indicate hip adduction moments. Unilateral loads were carried in the right hand.

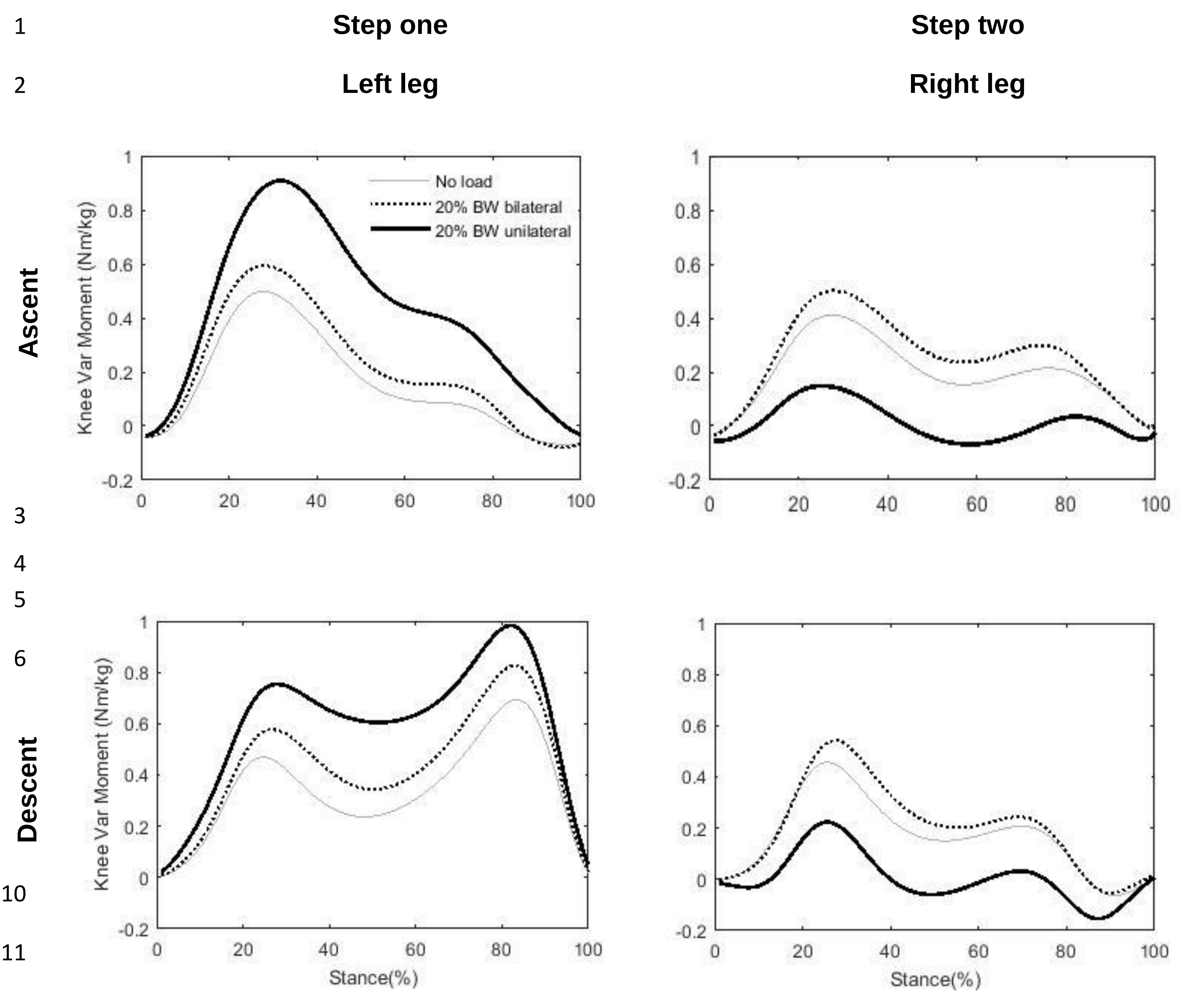

Figure 4. Ensemble curves for external knee varus moments during step one and step two of stair ascent and stair descent. Positive values indicate external knee varus moments, and negative values indicate external knee valgus moments. Unilateral loads were carried in the right hand.

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