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Carrying asymmetric loads during stair negotiation: Loaded limb stance vs. unloaded limb stance

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Abstract
Background

Individuals often carry items in one hand instead of both hands during activities of daily living. Research Question The purpose of this study was to investigate low back and lower extremity frontal plane moments for loaded limb stance and unloaded limb stance when carrying symmetric and asymmetric loads during stair negotiation.

Methods

Participants were instructed to ascend and descend a three-step staircase at preferred pace using a right leg lead and a left leg lead for each load condition: no load, 20% body weight (BW) bilateral load, and 20% BW unilateral load. L5/S1 contralateral bending, hip abduction, external knee varus, and ankle inversion moments were calculated using inverse dynamics.

Results

Peak L5/S1 contralateral bending moments were significantly higher when carrying a 20% BW unilateral load as compared to a 20% BW bilateral load for both stair ascent and stair descent. In addition, peak L5/S1 contralateral bending moments were significantly higher during step one than for step two. Peak external knee varus and hip abduction moments were significantly higher in unloaded limb stance as compared to loaded limb stance when carrying a 20% BW unilateral load.

Significance

General load carriage recommendations include carrying less than 20% BW loads and splitting loads bilaterally when feasible. Assessment recommendations include analyzing the first stair step and analyzing both the loaded and unloaded limbs.

Keywords
Gait, L5S1, Joint moments, Asymmetric load, Stair negotiation

Disciplines
Biomechanics | Kinesiology | Motor Control

Comments
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Significance

General load carriage recommendations include carrying less than 20% BW loads and splitting loads bilaterally when feasible. Assessment recommendations include analyzing the first stair step and analyzing both the loaded and unloaded limbs.

1. Introduction

Individuals frequently carry heavy items (e.g., suitcases or grocery bags) in one hand during activities of daily living. Carrying heavy loads in one hand can result in adverse changes in posture and how loads are distributed throughout the body during locomotion. Previous studies have reported that asymmetric load carriage increased trunk lateral bending angles [1, 2] and levels of perceived low back pain [3]. Other studies have found that carrying asymmetric loads with a bag resulted in higher hip abduction moments [4], a sidepack resulted in higher hip abduction and L5/S1 contralateral bending moments [5], and a hockey bag resulted in increased lower extremity muscle activation [6]. Therefore, asymmetric load carriage appears to increase frontal plane loading in both the low back and lower extremity.

Increased frontal plane loading has been associated with potential risk for development of knee osteoarthritis (OA) and low back injury. For example, persons with medial knee OA exhibited higher external knee varus moments than healthy controls [7, 8]. This change can lead to increased medial knee compartment compression and further thinning of articular cartilage [9]. An epidemiological study found that a 1% increase in external knee varus moments increased risk of knee OA progression by 6.46 times [10]. Furthermore, external knee varus moments remain higher even after total knee arthroplasty [11]. As a second example, increases in L5S1 lateral bending moments are linked to increased compressive and lateral shear loading

[12]. Increased intervertebral loading for a prolonged period can lead to rapid degeneration of the disc fibers [13]. Taken together, increased frontal plane loading in the low back and lower extremity when carrying asymmetric loads may be of concern for knee OA and low back injury.

When carrying a unilateral load, there is a larger moment arm from the load to the stance leg on the opposite side of the body (unloaded limb stance) as compared to the moment arm from the load to the stance leg on the same side of the body (loaded limb stance). Therefore, it is of interest to investigate if frontal plane joint moments are increased during unloaded limb stance. Matsuo et al. (2008) found higher hip abduction moments in unloaded limb stance when carrying a bag [4], and DeVita et al. (1991) found higher hip abduction and external knee varus moments during unloaded limb stance when carrying a sidepack during walking [5]. These studies investigated asymmetrical load carriage during walking, while the effects of asymmetrical load carriage on unloaded and loaded limb stance during stair negotiation remain unknown.

Stair ascent and descent require higher knee range of motion and knee extension moments than walking [14, 15]. Fewer studies have investigated load carriage during stair negotiation. For example, Hong and Li (2005) found that vertical ground reaction forces were higher for a 15% body weight (BW) load during stair descent and a 10% BW load during stair ascent when carrying asymmetric loads in a one-strap athletic bag [16]. Hall et al. (2013) reported higher external knee varus moments when carrying symmetric loads of approximately 20% BW during stair ascent as compared to walking and stair descent [17]. These findings support the ideas that stair negotiation is more demanding on the knees than walking, load carriage increases overall loading on the body, and asymmetric load carriage may further increase frontal plane knee joint moments.

The purpose of this study was to investigate low back and lower extremity frontal plane moments for loaded and unloaded limb stance when carrying symmetric and asymmetric loads during stair negotiation. We hypothesized that 1) peak external knee varus, hip abduction, and L5/S1 contralateral bending moments would be increased during unilateral load carriage as compared to bilateral load carriage, and 2) peak external knee varus and hip abduction moments would be significantly higher during unloaded limb stance as compared to loaded limb stance during unilateral load carriage.

2. Methods

Twenty-three healthy young adults with an age range of 20 to 30 (11 males/12 females; age 21.8 ± 2.4 years; height 173.3 ± 8.8 cm; mass 72.6 ± 12.6 kg) participated in this study. G*Power was used to calculate a sample size of 23 using previously published data [18] to determine a minimum estimated effect size of 0.96 with an alpha error probability of 0.0125 (adjusted by the number of variables) and a power of 0.90. Participants were free of any pathology that would affect them while walking on stairs or prevent them from being able to carry a 20% BW load. Individuals were excluded if they had back, neck, leg, foot, or arm pain. Prior to participation, each subject read and signed an informed consent document approved by the university's institutional review board.

Three load conditions were tested: no load, 20% BW bilateral load, and 20% BW unilateral load (Figure 1). The load was evenly split between the right and left hands during the bilateral load condition (10% BW in each hand). Two hand-held bags were filled with sealed bags of lead shot to match the loaded conditions. Since all participants were right-hand dominant, they carried the bag in the right hand during the unilateral load condition. The load carried in the bags was normalized according to each participant's body weight. The level of normalized load was based on the upper range of previous studies that indicated significant kinematic and/or kinetic changes when carrying loads ranging from 10% to 20% BW [5, 16, 19, 20].

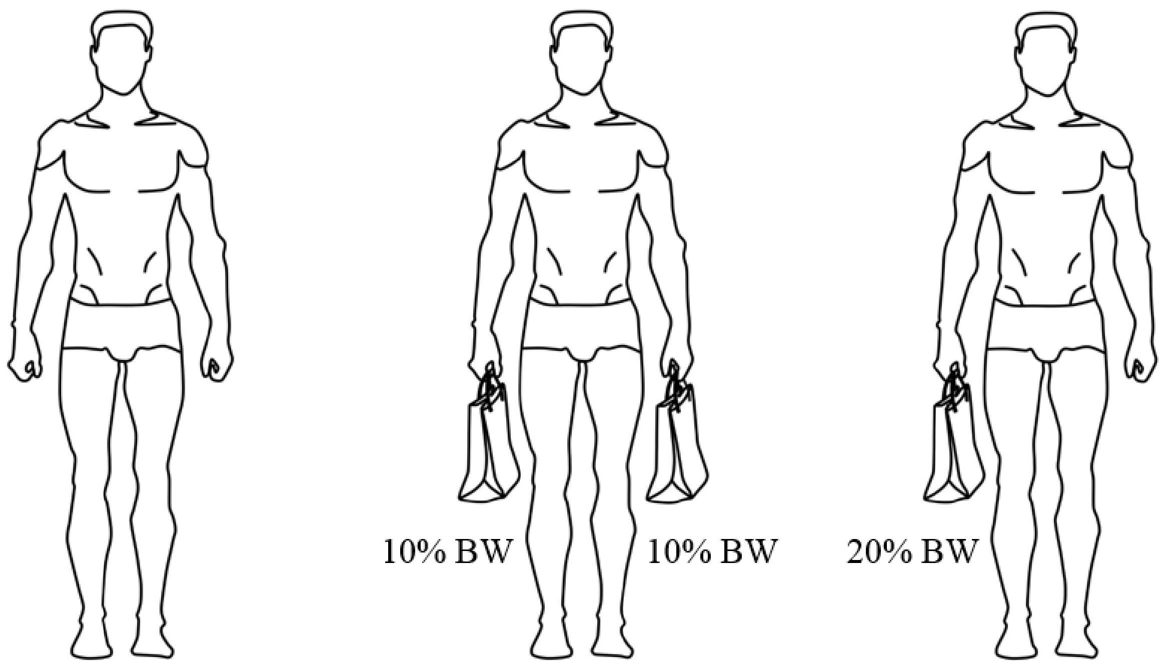


Fig. 1. Illustration of the three load conditions: no load (left), 20% BW bilateral load split between both sides of the body (center), and 20% body weight (BW) load on one side of the body (right).

Participants were instructed to ascend and descend a three-step staircase (step height 18.5 cm, tread depth 29.5 cm) at preferred pace using a right leg lead and a left leg lead for each load condition. The order of the conditions was randomized, and each condition was repeated three times for a total of 36 trials (3 load conditions × ascent/descent × right/left leg leads × 3 trials). Both a right and a left leg lead were tested to avoid results being biased by any differences in joint moments that might occur when comparing step one versus step two of stair negotiation.

Eight cameras (Vicon, Oxford, UK) were used to collect three-dimensional kinematic data. The dynamic marker set included bilateral great toe, lateral midfoot, lateral malleolus, anterior calf, lateral calf, lateral knee joint, anterior thigh, lateral thigh, greater trochanter, anterior superior iliac spine (ASIS), posterior superior iliac spine, and acromion process markers, along with a single sacrum and cervical maker. Six additional markers (bilateral heel, medial malleolus, and medial knee joint) were recreated using transformations determined from a static standing trial. Two force platforms (AMTI, Watertown, MA) placed on the first and second steps were used to collect kinetic data. Video data were sampled at 160 Hz, and force platform data were sampled at 1600 Hz. Video and force platform data were synchronized using Vicon Nexus (Vicon, Oxford, UK).

Video and force platform data were processed with a fourth-order, symmetric low-pass Butterworth filter at a cut-off frequency of 6 Hz. The force data were downsampled from 1600 to 160 Hz. Segment masses, center of mass (COM) locations, and moments of inertia were scaled to participant anthropometrics [21]. Frontal plane moments were of interest for comparing symmetric and asymmetric loads. L5/S1 contralateral bending, hip abduction, external knee varus, and ankle eversion moments were calculated using inverse dynamics. The location of the L5/S1 joint center was defined as 34% of the distance from the sacrum marker to the midpoint of the ASIS markers [22, 23].

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 due to a limited number of the force platforms. Thus, L5/S1 lateral bending moments were only analyzed during the single stance phase of the first and second steps corresponding to one left or right foot positioned on a force platform. A positive L5/S1 lateral bending moment was toward the unloaded stance leg or contralateral side of the body during unilateral load carriage. Hip abduction and external knee varus moments (opposite in sign to internal knee valgus moments) were analyzed during the entire stance phase of the first and second steps. Peak joint moments were determined and normalized by body mass. All calculations were performed using a custom Matlab code.

After checking assumptions of multivariate normality, correlations, and sphericity, the effects of load and step on peak moments were analyzed using a repeated measures MANOVA (3×2). Univariate repeated measures Analyses of Variance (ANOVAs) were performed when main effects of the MANOVA were significant. Bonferroni post-hoc adjustments were used for multiple comparisons. To investigate the effect of the loaded limb vs. the unloaded limb stance during 20% unilateral load carriage, the Hotelling test was performed. Paired t-tests were used when a main effect of the Hotelling test was significant. The level of statistical significance for all tests was set at $\alpha < 0.05$. Statistical analyses were performed using SPSS.

3. Results

3.1 Stair ascent

MANOVA revealed a significant main effect of load ($p < 0.001$). Univariate ANOVA indicated main effects of load on peak L5/S1 contralateral bending, hip abduction, external knee varus, and ankle inversion moments (Table 1). L5/S1 contralateral bending, hip abduction, and external knee varus moments were higher for the 20% unilateral load than the 20% bilateral load or no load ($p \leq 0.016$). In addition, hip abduction, external knee varus, and ankle eversion moments were higher for the 20% bilateral load than no load ($p \leq 0.002$). MANOVA also revealed a main effect of step ($p < 0.001$). Univariate ANOVA indicated that L5/S1 contralateral bending, hip abduction, external knee varus, and ankle inversion moments were higher during step one than step two (Table 1).

Table 1. Peak mean and standard deviations for joint moments during stair ascent and statistical results from univariate ANOVAs.

	Stair ascent					Main effect		
	No load Mean (SD)	Bilateral Mean (SD)	Unilateral Mean (SD)	Step 1 Mean (SD)	Step 2 Mean (SD)	Load *p* (power)	Step *p* (power)	Load × Step *p* (power)
L5/S1 contralateral bending (Nm/kg)	0.160 (0.109)	0.153 (0.118)	**0.600ab** **(0.162)**	**0.385c** **(0.256)**	0.223 (0.210)	**<0.001*** **(1.000)**	**<0.001*** **(1.000)**	**0.001*** **(0.948)**
Hip abduction (Nm/kg)	0.817 (0.121)	**0.967a** **(0.143)**	**1.008ab** **(0.143)**	**0.950c** **(0.153)**	0.912 (0.162)	**<0.001*** **(1.000)**	**0.015*** **(0.715)**	0.065 (0.534)
External knee varus (Nm/kg)	0.455 (0.129)	**0.521a** **(0.142)**	**0.557ab** **(0.139)**	**0.545c** **(0.133)**	0.477 (0.144)	**<0.001*** **(1.000)**	**<0.001*** **(0.999)**	0.282 (0.245)
Ankle inversion (Nm/kg)	0.104 (0.048)	**0.134a** **(0.071)**	**0.119a** **(0.053)**	**0.128c** **(0.057)**	0.110 (0.060)	**<0.001*** **(0.979)**	**0.001*** **(0.972)**	0.319 (0.195)

	Stair descent					Main effect		
	No load Mean(SD)	Bilateral Mean(SD)	Unilateral Mean(SD)	Step 1 Mean(SD)	Step 2 Mean(SD)	Load *p* (power)	Step *p* (power)	Load × Step *p* (power)
L5/S1 contralateral bending (Nm/kg)	0.439 (0.147)	0.448 (0.148)	**0.852ab** **(0.177)**	**0.662c** **(0.233)**	0.498 (0.238)	**<0.001*** **(1.000)**	**<0.001*** **(1.000)**	**0.011*** **(0.784)**
Hip abduction (Nm/kg)	1.013 (0.105)	**1.192a** **(0.113)**	**1.166a** **(0.144)**	1.094 (0.141)	**1.153d** **(0.143)**	**<0.001*** **(1.000)**	**0.003*** **(0.884)**	**0.024*** **(0.671)**
External knee varus (Nm/kg)	0.591 (0.141)	**0.689a** **(0.145)**	**0.676a** **(0.189)**	0.669 (0.171)	0.635 (0.157)	**<0.001*** **(0.999)**	0.630 (0.464)	0.922 (0.058)
Ankle inversion (Nm/kg)	0.127 (0.054)	0.139 (0.051)	**0.145a** **(0.054)**	0.127 (0.054)	**0.146d** **(0.051)**	**0.003*** **(0.899)**	**0.004*** **(0.870)**	0.747 (0.087)

*indicates $p < 0.05$, ‘a’ indicates significant difference when compared to no load, ‘b’ indicates significant difference when compared to 20% BW bilateral loads, ‘c’ indicates significant difference when compared to step 2; ‘d’ indicates significant difference when compared to step 1

A significant interaction of load and step was found for peak L5/S1 contralateral bending moments (Table 1). Therefore, simple effects for each combination of load and step were tested. L5/S1 contralateral bending moments were higher for the unilateral than the bilateral load and no load for both step one and step two ($p < 0.001$). L5/S1 contralateral bending moments were also significantly higher for step one than step two for all load conditions ($p < 0.001$). Therefore, the main effects held true for all interaction combinations.

The Hotelling test revealed a significant main effect of stance limb ($p < 0.001$). Paired t-tests indicated that external knee varus and hip abduction moments were higher for the unloaded than the loaded stance limb ($p < 0.001$, Figure 2a). Ensemble curves illustrating external knee varus and hip abduction moments of the unloaded and loaded stance limb during stair ascent are shown in Figure 3.

3.2 Stair descent

MANOVA revealed a significant main effect of load ($p < 0.001$). Univariate ANOVA indicated main effects of load on L5/S1 contralateral bending, hip abduction, external knee varus, and ankle inversion moments (Table 1). L5/S1 contralateral bending, hip abduction, external knee varus, and ankle inversion moments were higher for the unilateral load than no load ($p < 0.001$). L5/S1 contralateral bending moments were also higher for the unilateral than the bilateral load ($p < 0.001$). In addition, hip abduction and external knee varus moments were higher for the bilateral load than no load ($p < 0.001$). MANOVA also revealed a main effect of step ($p < 0.001$). Univariate ANOVA indicated that L5/S1 contralateral bending moments were higher during step one than step two, while hip abduction and ankle inversion moments were higher during step two than step one (Table 1).

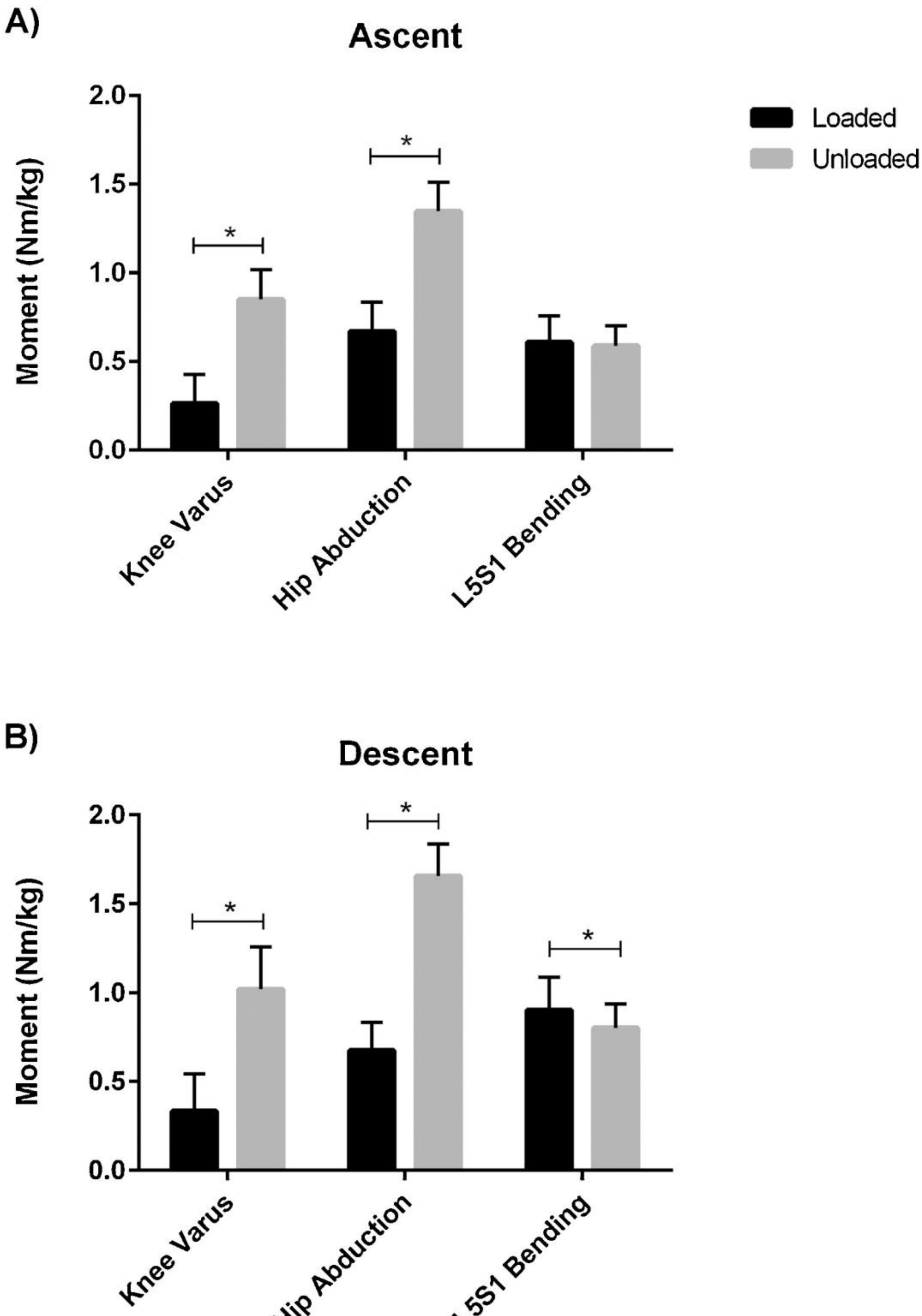


Fig. 2. Effects of loaded limb stance vs. unloaded limb stance on external knee varus, hip abduction, and L5/S1 contralateral bending moments during ascent (A) and descent (B).

* indicates a significant difference ($p < 0.001$).

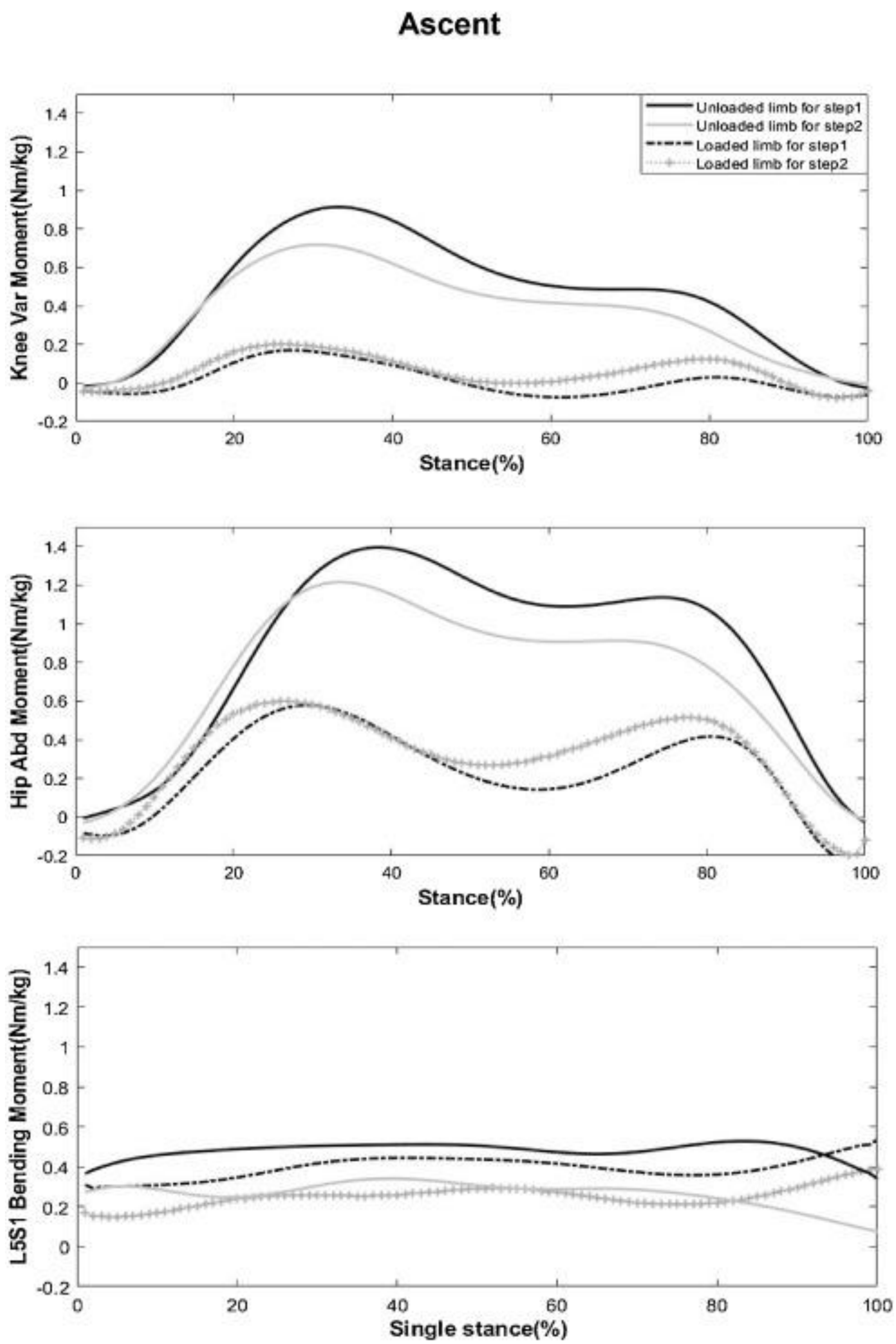
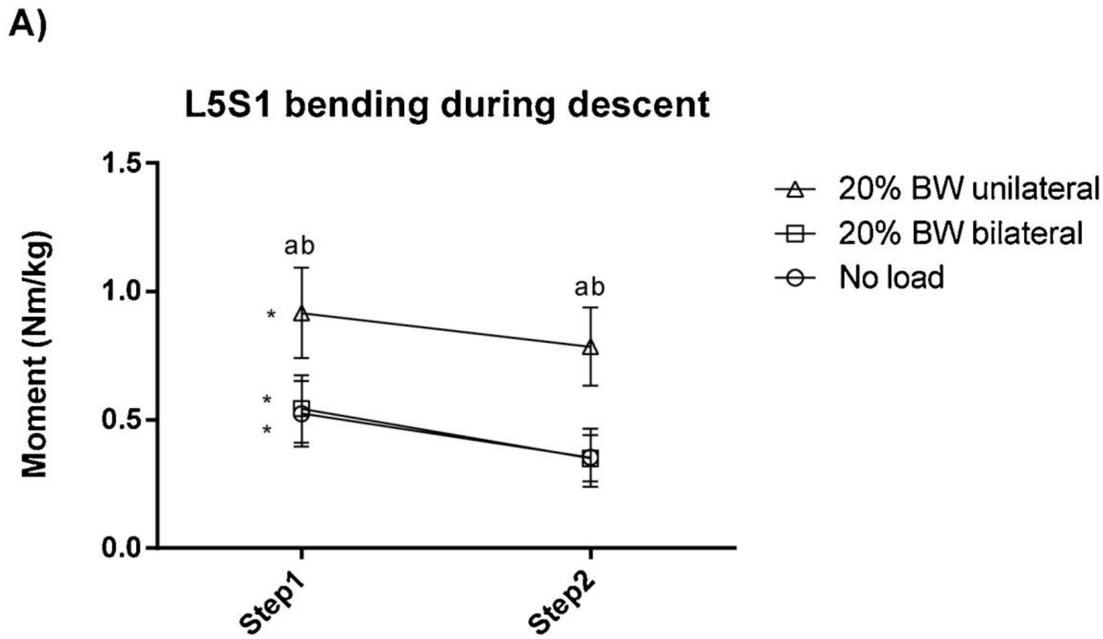


Fig. 3. Ensemble curves of external knee varus, hip abduction, and L5/S1 contralateral bending moments for the 20% BW unilateral load during stair ascent.

A significant interaction of load and step was found for peak L5/S1 contralateral bending and hip abduction moments (Table 1). L5/S1 contralateral bending moments were higher for the unilateral than the bilateral load and no load for both step one and step two ($p < 0.001$, Figure 4a). L5/S1 contralateral bending moments were also higher for step one than step two for all load conditions ($p < 0.001$). Therefore, L5/S1 contralateral bending moment main effects held true for all interaction combinations. Hip abduction moments were only higher for step two than step one for the unilateral load ($p < 0.001$), but not for the bilateral load or no load (Figure 4b).

The Hotelling test revealed a significant main effect of stance limb ($p < 0.001$). Paired t-tests indicated that peak L5/S1 contralateral bending moments were higher for the loaded stance limb, while external knee varus and hip abduction moments were higher for the unloaded stance limb ($p < 0.001$, Figure 2b). Ensemble curves illustrating L5/S1 contralateral bending, external knee varus, and hip abduction moments for the unloaded and loaded stance limb are shown in Figure 5.



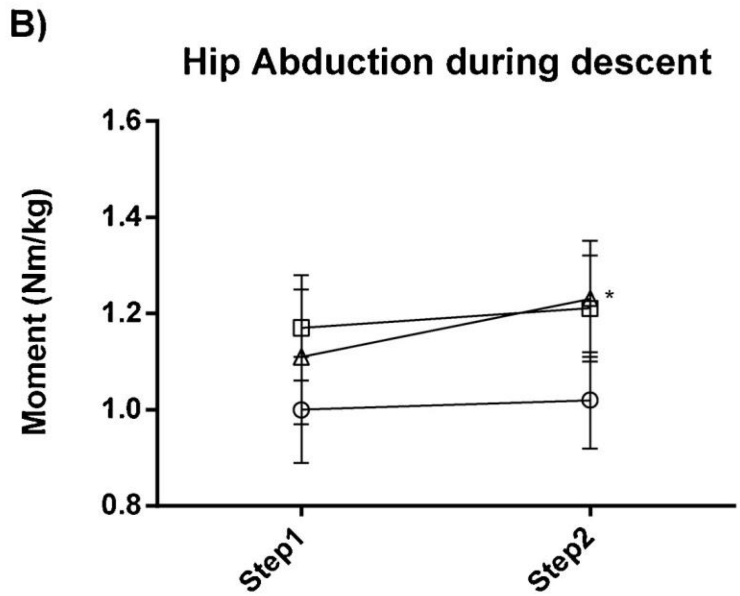


Fig. 4. Results of simple main effects for L5/S1 contralateral bending (A) and hip abduction (B) moments during stair descent. The simple main effects were tested for each combination of load and step due to a significant interaction. * indicates a significant difference between step 1 and step 2; ‘a’ indicates a significant difference when compared to no load; ‘b’ indicates a significant difference when compared to 20% BW bilateral load.

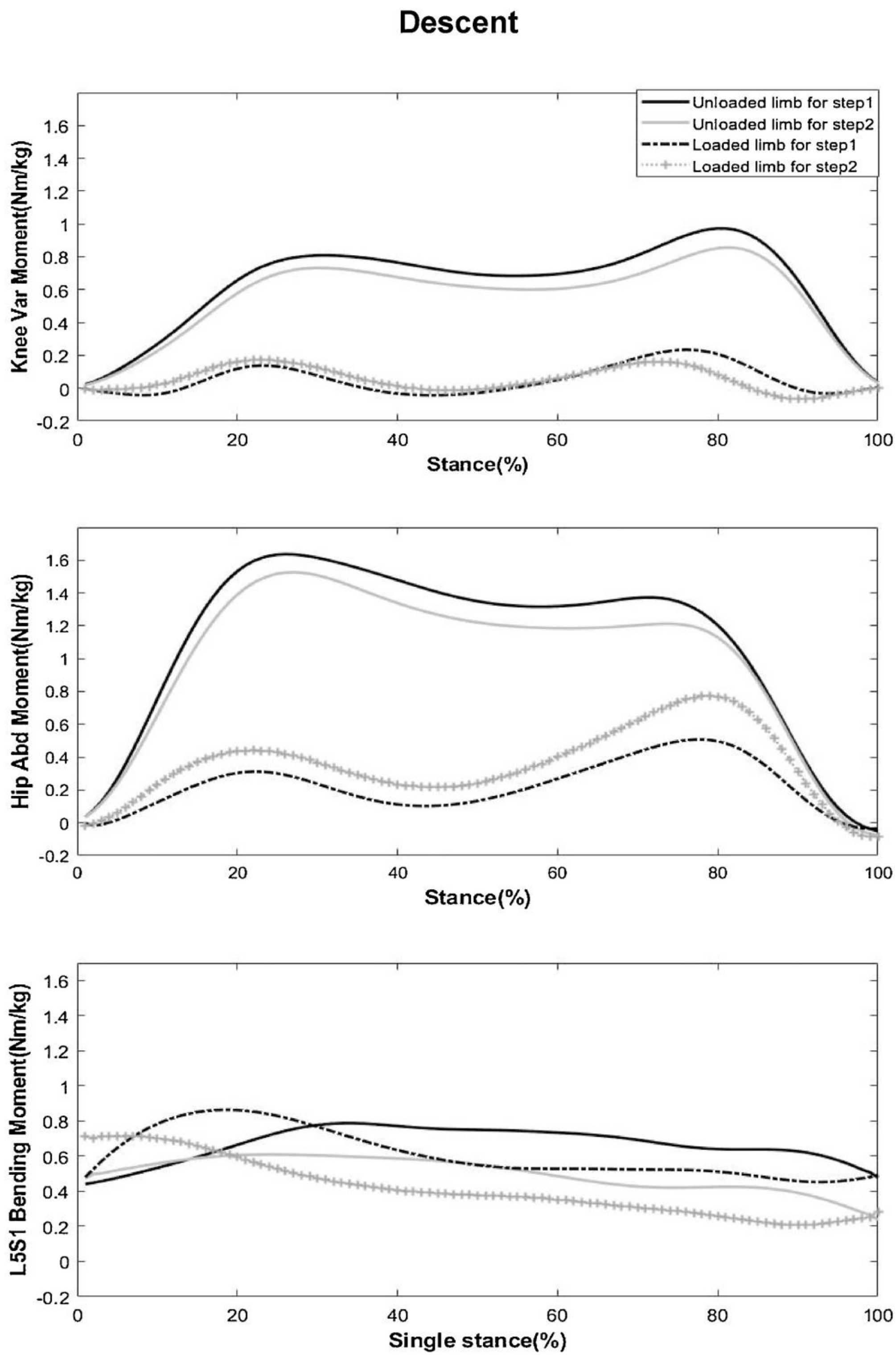


Fig. 5. Ensemble curves of external knee varus, hip abduction, and L5/S1 contralateral bending moments for 20% BW unilateral load during stair descent.

4. Discussion

The purpose of this study was to investigate the effect of load symmetry on low back and lower extremity frontal plane moments for loaded and unloaded limb stance when carrying symmetric and asymmetric loads during stair ascent and stair descent.

4.1 Stair ascent

Our first hypothesis that external knee varus, hip abduction, and L5/S1 contralateral bending moments would be increased during unilateral as compared to bilateral load carriage was supported during stair ascent (Table 1). These results indicate that the external load imbalance introduced by unilateral load carriage is reflected in the frontal plane joint moments. The L5/S1 appeared to be particularly sensitive to load asymmetry as the contralateral moments were unchanged when comparing a 20% BW bilateral load to no load. Increased L5/S1 lateral bending moments may lead to increased risk for low back pain or injury. For example, increases in lateral bending moments are associated with increased compressive and shear forces on the intervertebral discs and ligaments [12]. McGill et al. (2013) reported that asymmetric load carriage with a 30 kg bucket in one hand resulted in higher compressive spinal loading as compared to bilateral load carriage with 30 kg buckets in both hands during walking [24]. Schmidt et al. (2007) demonstrated that lateral bending moments combined with axial moments may contribute to failure of intervertebral discs [13]. Therefore, our results suggest that when feasible, it is beneficial to split a unilateral load into bilateral loads to reduce low back loading.

Our second hypothesis that external knee varus and hip abduction moments would be higher for unloaded limb stance during unilateral load carriage was supported for stair ascent (Figure 2a). In fact, hip abduction moments were over 100% higher and external knee varus moments were over 200% higher during unloaded limb stance. These results are likely explained by greater frontal plane moment arms from the center of pressure of the unloaded limb to the unilateral load. Similar patterns have been observed when carrying a 20% BW one-strap sidepack during normal walking [5]. Also, Neumann (1996) reported higher hip abductor muscle activation in the unloaded limb when carrying 15% BW unilateral loads as compared to no load [25]. In addition, increased hip abduction moments may result in higher compressive forces in the articular joint surface and lead to joint degeneration [26]. Increased external knee varus moments are associated with increased compressive loading in the medial knee joint compartment [7] and thus can be of concern for development of chronic knee pain or osteoarthritis [7, 8]. A finite element study demonstrated that increased external knee varus moments also resulted in higher ACL strain [27]. Therefore, the results suggest that asymmetric load carriage tasks may involve higher injury risk for the unloaded leg during stair ascent. This effect appeared to be limited to the lower extremity as L5/S1 bending moments were not higher during unloaded leg stance.

Frontal plane moments were higher during the first step of stair ascent (Table 1). The initial step of stair ascent is often considered a transition from standing or walking to a repeating pattern of stair negotiation. Higher joint moments during the first step suggest the importance of measuring this transition when analyzing stair ascent. L5/S1 contralateral bending moments were highest when carrying a 20% BW unilateral load during step one. Ensemble curves illustrate that peak external knee varus and hip abduction moments occurred in the unloaded leg with a 20% BW unilateral load during 20-40% of stance during step one (Figure 3).

4.2 Stair descent

Our first hypothesis that frontal plane moments would be increased during unilateral as compared to bilateral load carriage was only supported for L5/S1 contralateral bending moments during stair descent (Table 1). Similar to stair ascent, the L5/S1 appeared to be sensitive to load asymmetry as the contralateral moments were unchanged when comparing a bilateral to no load. When examining Tables 1 and 2, stair descent resulted in higher peak frontal plane moments than stair ascent for all loading conditions. These results suggest the relative difficulty of both loaded and unloaded stair descent as compared to ascent.

Our second hypothesis that external knee varus and hip abduction moments would be higher for unloaded limb stance during unilateral load carriage was supported for stair descent (Figure 2b). The differences were again substantial, with hip abduction moments 140% higher and external knee varus moments over 200% higher during unloaded limb stance. As with stair ascent, these results are likely explained by larger frontal plane moment arms from the center of pressure of the unloaded limb to the unilateral load. Thus, unilateral load carriage would produce asymmetric joint loading between the loaded and unloaded limbs, which may lead to pathologic changes and higher incidence of knee and hip osteoarthritis [7, 8, 26].

In contrast, L5/S1 contralateral bending moments were higher during loaded limb stance. This may indicate that the lower extremity and low back play different roles in adjusting to asymmetric loads during stair descent, with the lower extremity playing a larger role during unloaded limb stance and the low back playing a larger role during loaded limb stance. For instance, hip abduction moments may be utilized to maintain the COM within the base of support [28] during unloaded stance. On the other hand, upper body adjustments may be required when the COM is close to the base of support during loaded limb stance.

L5/S1 contralateral bending moments were higher during the first step, while hip abduction moments were higher during the second step of stair descent (Table 1, Figure 4). These results may further support different roles of the lower extremity and low back, although the effect of unloaded versus loaded limb stance was much greater than the effect of step number for hip abduction moments. Ensemble curves illustrate that L5/S1 contralateral bending moments were highest in loaded limb stance when carrying a unilateral load during step one of stair descent (Figure 5). Hip abduction moments were highest in unloaded limb stance when carrying a unilateral or bilateral load during step two.

There are several limitations of this study. One limitation is that a three step staircase was used, so the participants may not have achieved a repeatable stair negotiation pattern. However, the results indicated the importance of considering the first step of stair ascent and descent. If considering load carriage guidelines, another limitation is that only 20% BW loads were tested. With significant differences occurring at 20% BW loads, it is unclear if a 10% or 15% BW load would have also resulted in significant differences.

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