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The Effect of Load Magnitude and Distribution on Lumbar Spine Posture in Active-Duty Marines

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No relevant financial activities outside the submitted work.

Study Design: Repeated measures.

Objective: The purpose of this study was to quantify the effect of operationally relevant loads and distributions on lumbar spine (LS) in a group of active-duty Marines.

Summary of Background Data: Low back pain has been associated with heavy load carriage among military personnel. Although there are data describing the LS posture in response to load, the effect of varying load characteristics on LS posture remains unknown.

Methods: MRI images of Marines (n=12) were acquired when standing unloaded and while carrying 22, 33 and 45kg of load distributed both 50%-50% and 20%-80% anteriorly and posteriorly.Images were used to measure LS and pelvic postures.Two-way repeated-measures ANOVA and post-hoc tests were used to compare LS posture across load magnitudes and distributions ($\alpha=0.05$).

This project was founded by the U.S. Army Medical Research Acquisition Activity, Award No. W81XWH-13-2-0043, under Work Unit No. 1310.

Results: No changes in LS posture were induced when load was evenly distributed. When load was carried in the 20%-80% distributionlumbosacralflexion increased as a result of sacral anterior rotation and overall reduced lumbar lordosis. This pattern was greater as load was increased between 22 and 33kg, but did not increase further between 33 and 45kg.We observed that the inferior LS became uniformly less lordotic, independently of load magnitude. However, the superior LS became progressively more lordotic with increasing load magnitude

Conclusions: Postural adaptations were found only when load was carried with a posterior bias, suggesting that load-carriage limits based on postural changes are relevant when loads are non-uniformly distributed. Although the tendency would be to interpret that loads should be carried symmetrically to protect the spine, the relationship between postural changes and injury are not clear. Finally, the operational efficiency of carrying load in this distribution needs to be tested.

Key Words:military; load carriage; posture; lumbar spine; sacral slope; load magnitude; load distribution

Level of Evidence:3

Introduction

Back problems represent a major health and economic burden among military personnel, as they are the primary cause for medical encounters and lost work time (1). The incidence of moderate or severe low back pain (LBP) after a one year deployment to Afghanistan is around 22% (2). Among soldiers, a questionnaire study revealed that the relative risk of developing LBP increased as a function of the magnitude of the carried load (2). Military personnel carry loads of up to 68kg depending on duty position and nature of the mission (3). These loads are necessary to maintain soldiers' safety and to successfully fulfill their missions. Consequently, the effect of heavy load carriage on energy expenditure, situational awareness and combat readiness has been extensively studied (4-6). Contrastingly, postural data of the musculoskeletal components of the lumbar spine (LS) during load carriage is limited. In previous work from our group, we quantified the deformation of the LS when carrying 50.8kg in a group of active-duty Marines (7). These data indicated that heavy load carriage induced lumbosacral flexion and forward trunk lean. Other authors have described LS postural changes when carrying backpacks with increasing load magnitudes in the 10-30% of body weight (BW) range. However, these data have been measured in a pediatric population using different loads, which may not be representative of military personnel and operational conditions (9, 10). Postural adaptations of the LS in response to load magnitudes and different anterior-posterior distributions have not been systematically studied in a military population.

This information may allow identifying potential LS injury mechanisms associated with load carriage and contribute to developing load carriage systems and limit recommendations based on measurable changes in LS posture. Both pieces of information may inform best practices to minimize LS injuries. Therefore, the purpose of this study was to quantify the effect of operationally relevant loads and distribution on LS posture in active-duty Marines. We hypothesize that when loads are evenly distributed anterior and posteriorly, the deviation from the standing posture would be small compared to loads carried with a posterior bias. Additionally, we hypothesize that as load magnitude increases lumbar lordosis would decrease and lumbosacral flexion would increase.

Materials and Methods

Subjects

Twelve active-duty Marines (mean±SD age, 23.41±4.71 years; height, 177.8±5.41 cm; weight, 76.77±11.32 kg; body mass index, 24.15±2.19 kg/m^2) from the Marine Corps Base Camp Pendleton volunteered in this study. The average time of service of this group was 48±39.96 months and their occupations were all of the infantry rating (1 officer, 8 riflemen, 2 machine gunners, 2 assault men, and 1 unit leader). The University of California, San Diego and Naval Health Research Center institutional review boards approved this study. All volunteers provided oral and written informed consent.

Imaging

Marines were scanned using an upright 0.6T magnetic resonance imaging (MRI) scanner (UPRIGHT® Multi-Position MRI, Fonar Corporation, Melville, NY) and flexible planar coil. A soft sleeve was used to retain the coil posteriorly at the LS level. During loaded scans, the coil was placed between the volunteer's back and load carriage system. A localizer and sagittal T2 weighted images (repetition time 1974 msec; echo time 160 msec; field of view 32 cm; 1.56×1.56 mm^2 pixel size; 4.5mm slice thickness; 0.5 mm gap; scan duration 2:30 minutes) were acquired.

Load-Carrying Tasks

Marines were scanned standing unloaded (Fig. 1A) and while carrying 22, 33 and 45kg of load distributed both 50%-50% (Fig. 1B-D) and 20%-80% (Fig. 1E-G) anteriorly and posteriorly (AP), respectively. The first scan was always standing unloaded and the other 6 scans were randomized for all participants. Marines were not given instructions on how to stand, but were instructed to remain still during image acquisition.

Load magnitudes of 22kg and 33kg were selected because they are the recommended load carriage limits for fighting and approach march loads, respectively (6). Additionally, 45kg is on the lower end of sustainment loads carried by Marines during dismounted operation in Afghanistan (11). The 50-50% and 20-80% AP load distributions were selected based on preliminary data (not shown) indicating that when loads are light (i.e. average 12.3kg) they are carried evenly. Moreover, it has been previously hypothesized that this load distribution induces minimal postural changes in the LS; therefore, we tested this concept (12). Further, heavier loads are typically carried using a backpack. This load carriage paradigm has been reported to induce postural changes that progressively deviate from the standing posture as a function of load magnitude (12, 13). Typically, load carried anteriorly is in the form of small pouches attached to the body armor; therefore. Marines wore a body armor.

Data Analysis

Each data set was analyzed as previously described (7, 8). Briefly, a set of markers was manually placed at the corners of each vertebra (L1–S1) on all sagittal images, and on posterior elements on a single axial image per lumbar level. These data were used to describe vertebral endplate orientation.

Measurements

Postural measurements of the LS in the sagittal plane were generated based on vertebral endplates orientation. Angle with respect to the horizontal was defined as the angle between the centroid of L1, S1 and the horizontal line; it quantifies lumbosacral flexion. A relationship between LS posture and *sacral slope (SS)* has been previously reported (14, 15). Therefore, to estimate the contribution of the pelvis to load carriage postural adaptations the SS was also measured. Sacral slope is defined as the angle between the superior endplate of S1 and the horizontal, which describes the orientation of the sacrum.

Lumbar lordosis was measured using Cobb angle, defined it as the angle between the superior endplates of L1 and S1 in the sagittal plane. (16-18). Due to the disparate behavior among the superior and inferior LS during load carriage,(7) we defined the superior sagittal Cobb angle as the angle formed by the superior endplate of L1 and the inferior endplate of L3, and the inferior sagittal Cobb angle as the angle between the inferior endplates of L3 and S1 (7).

Intervertebral disc (IVD) angles and regional heights were measured between the planes of the inferior and superior endplates of adjacent vertebrae. Intervertebral heights were measured as the shortest distance between these endplates anteriorly, centrally, and posteriorly.

Postural adaptations to load carriage have been hypothesized to realign the center of gravity (CoG) over the base of support. Determining the system's CoG requires knowledge of the position and mass of the body segments (19). This information was not available and the use of x-rays was not approved. However, it has been shown that during static activities the location of the center of pressure (CoP) and CoG with respect to the base of support are highly correlated (19). Therefore, the CoP was measured using a pressure mat (Tekscan In., South Boston, MA). Ideally, these measurements would be made during MRI acquisition; however, due to the ferromagnetic components of the mat, this was not possible. Alternatively, a mock scanner with identical dimensions as the upright MRI scanner was built and the pressure mat was placed between the structure's wall. After the image acquisition for each configuration, Marines were asked to step on the mat and stand still for one minute. A minimum bounding box (MBB, Fig. 2A) is defined as the smallest rectangle that can fit all points of a determined dataset, in this case, the footprints (20). This analysis allowed to account for the differences in feet position and size. The location of the CoP was expressed as the percentage of length and width of the MBB.

Statistical Analysis

All variables were compared using two-way repeated-measures analyses of variance (ANOVA) with Sidak *post-hoc* tests to identify significant differences as a function of load magnitude and distribution. The comparison between each load carriage distribution (50%-50% or 20%-80%) and the unloaded condition were identified using one-way repeated-measures ANOVA with Sidak *post-hoc* tests (α=0.05). Statistical analyses were performed using SPSS Statistics software (version 20.0, IBM, Armonk, NY). All data are reported as mean ± standard deviation values.

Results

Measurement of the CoP Location

The average location of the CoP along the width (left to right) of the BMM was 46.78±4.91% and 46.38±6.06% along the height (posterior to anterior). There was no significant difference in the location of the CoP between configurations (Fig. 2B).

Measurement of Lumbar Spine Load-Carriage Postural Changes

The effect of load carriage on LS posture is both magnitude and distribution dependent ($p<0.05$). Loads carried in the 50%-50% distribution did not have an effect on LS posture. Contrastingly, the overall position of the LS was significantly more horizontal in the 20%-80% distribution compared to standing unloaded (82.28±4.14°; Fig. 3, solid bars). More specifically, these changes were significant different only when carrying 33kg and 45kg, but not when carrying 22kg (75.23±7.79°, Fig. 3, asterisks). Interestingly, lumbosacral flexion values when carrying 33kg and 45kg were not different from each other (64.77±7.91° and 62.62±9.36°).

Sacral slope measurements had a similar response to load magnitude and distribution as lumbosacral flexion. In general, when loads were carried in the 20%-80% distribution the orientation of the sacrum became more horizontal (Fig. 4, solid bars). However, only 33kg and 45kg load magnitudes had a significant effect on sacrum orientation compared to standing without external load (34.29±6.59°) and were not different from each other (46.40±6.40° and 50.76±8.35°; Fig. 4, asterisks).

Whole LS lordosis (L1-S1) was also influenced by both load magnitude and distribution ($p<0.05$); however, *post-hoc* tests revealed no differences between load magnitudes (Fig. 5A). Overall, the LS became less lordotic ($p<0.05$) when carrying load in the 20%-80% distribution. Contrary to our initial hypothesis, only when carrying 22kg, lumbar lordosis deviated from that of standing without external load (Fig. 5A). No changes were found in whole LS lordosis when carrying

33 and 45kg. However, regional lordosis measurements revealed that the upper and lower lumbar spine behave differently.

Both load magnitude and distribution had a significant effect on superior LS lordosis ($p<0.05$). Superior LS became more lordotic when carrying 33 and 45kg in the 20%-80% distribution (17.80±6.28° and 16.88±5.49°) compared to the standing unloaded (10.49±5.18°, Fig. 5B, asterisks). The lordosis of the inferior LS was found to be affected solely by load distribution ($p<0.05$). Interestingly, the inferior LS became straighter (~10°) independently of load magnitude when load was carried with a posterior bias (Fig. 5C, solid bars).

In agreement with the changes in regional lordosis, load magnitude had a significant effect on superior levels, while load distribution influenced inferior levels (Sup. Fig. 1). More specifically, L1-L2 IVD became more lordotic as load increased, again, no differences were found between 33kg and 45kg. At the L2-L3 level, both load magnitude and distribution had an effect on local lordosis ($p<0.05$), however, *post hoc* tests revealed no differences between load magnitudes. A significant interaction between load magnitude and distribution was found at the L3-L4 level. At L4-L5 and L5-S1 levels a significant effect of load distribution was observed. Both levels became less lordotic in the same amount independently of load magnitude.

Similar results were observed for changes in regional IVD distances, which reflect postural changes in IVD angle throughout lumbar levels (Figs. S2). For example, when a functional spinal unit became less lordotic in response to load carriage, anterior IVD distances decreased and posterior IVD distances increased.

Discussion

The objective of this study was to measure the postural changes of the LS in response to operationally relevant load carried magnitudes and distributions. We hypothesized that the postural deviation of the LS when carrying load in a posterior bias would be larger than when the load was evenly distributed. Our results showed that independently of load magnitude, the LS posture was not different from that when standing without external load when carried in an even distribution. Additionally, when load was carried with a posterior bias, lumbosacral flexion progressively increased. Interestingly, when a load of 22kg was carried in this distribution the only postural difference in the LS is at inferior lumbar levels. Furthermore, the lack of differences between 33 and 45kg suggests a postural adaptation plateau, indicating the contribution of active components of the musculoskeletal system to maintain the load carriage posture.

The observed increased lumbosacral flexion appears to result from the contribution of two postural mechanisms: anterior sacral rotation and reduced lordosis. Both SS and lumbar lordosis have been previously measured during load carriage using motion capture and springs (12, 21-24). However, in the present study we have measured these variables directly. Previously reported values of pelvic rotations were described as linear displacements and range of motion making it impossible to compare to our results. Additionally, Birrell et al showed that pelvic rotation linearly increased as a function of load magnitude (25).

In previous work from our group Marines carried 50.8kg in a backpack and found reduced lordosis. In the present study, our results show that lumbar lordosis was significantly decreased only when carrying the lightest load and was not different when carrying the heavier loads. We attribute this partially to the difference in load magnitude (~6kg), but mostly to the disparity in load distribution. In the present study, a total load of 45kg in the 20%-80% distribution means that 36kg were carried posteriorly, which is much smaller compared to 50.8kg carried mostly posteriorly. This emphasizes the importance of load distribution, suggesting that careful attention should be given to this parameter in load carriage recommendations.

In order to understand the several components of the overall LS posture, we measured regional and local lordosis. In agreement with our previous work, we found that when load is carried with a posterior bias, superior and inferior LS have opposite postural adaptations to load (7). Surprisingly, inferior LS lordosis was reduced by the same amount (~10°) independently of load magnitude. Simultaneously, the overall orientation of the LS was also more horizontal. This may suggest that it is the orientation of the inferior LS that determines the response of the superior LS to load, which is load dependent. We propose that this postural adaptation aims to maintain the rest of the trunk and head in a vertical position.

Intervertebral disc angles revealed that when standing without external load, lumbar lordosis increases caudally, and during load carriage it increases cranially. In agreement with our previous work, the L3-L4 lumbar level behaved as a transition level between the superior and inferior LS. Furthermore, we compared local lordosis when carrying ~22kg in the 20%-80% distribution from the present study to another work from our group (unpublished data) where Marines carried the same amount of load in a similar distribution without body armor. We found that when carrying this load magnitude, the use of body armor did not affect lordosis distribution. However, the effect of body armor at heavier loads remains to be investigated as it may alter both trunk and LS kinematics during load carriage.

An additional factor contributing to the LS posture during load carriage is the location of the load CoG in the superior-inferior direction. Although this was not measured in this experiment, its effect on overall trunk flexion has been previously studied (26, 27). The response in trunk flexion has been shown to be larger when loads are carried more inferiorly, potentially leading to increased energy expenditure and paraspinal muscles contraction (26). Reducing trunk flexion during load carriage would also result in reduced moments around all lumbar levels (biomechanical analysis not shown). These data may suggest that carrying load more superiorly has several advantages in terms of LS biomechanics and energy expenditure. However, further field studies are needed to incorporate LS biomechanics in response to load into military recommendations. For example, subjects with load carriage experience report that during marches carrying load superiorly is more unstable (more sway) and that this effect is increased in uneven terrains (27).

In conclusion, when Marines carry load in an evenly distribution no postural changes were detected. However, the interpretation of these data should be limited because whether this means that this load distribution is more protective of the LS compared to a posteriorly biased distribution is unknown. During load carriage with a posterior bias, the position of the LS with respect to the ground was more horizontal. This resulted from anterior pelvic rotation and overall reduced lordosis; however, on average, all lumbar levels remained in flexion. Further research is needed to investigate the adaptation of other musculoskeletal tissues to different degrees of lordosis and how this might vary throughout lumbar levels as they are morphologically different. These data would allow narrowing down potential mechanisms of injury and to adjust physical training to further prevent low back-related injuries.

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Figure Legends

Figure 1 – Representative pictures of a Marine standing A) without external load, and carrying 22kg (B and E), 33kg (C and F), and 45kg (D and G) in the 50%-50% (top row) and 20%-80% (bottom row) distributions.

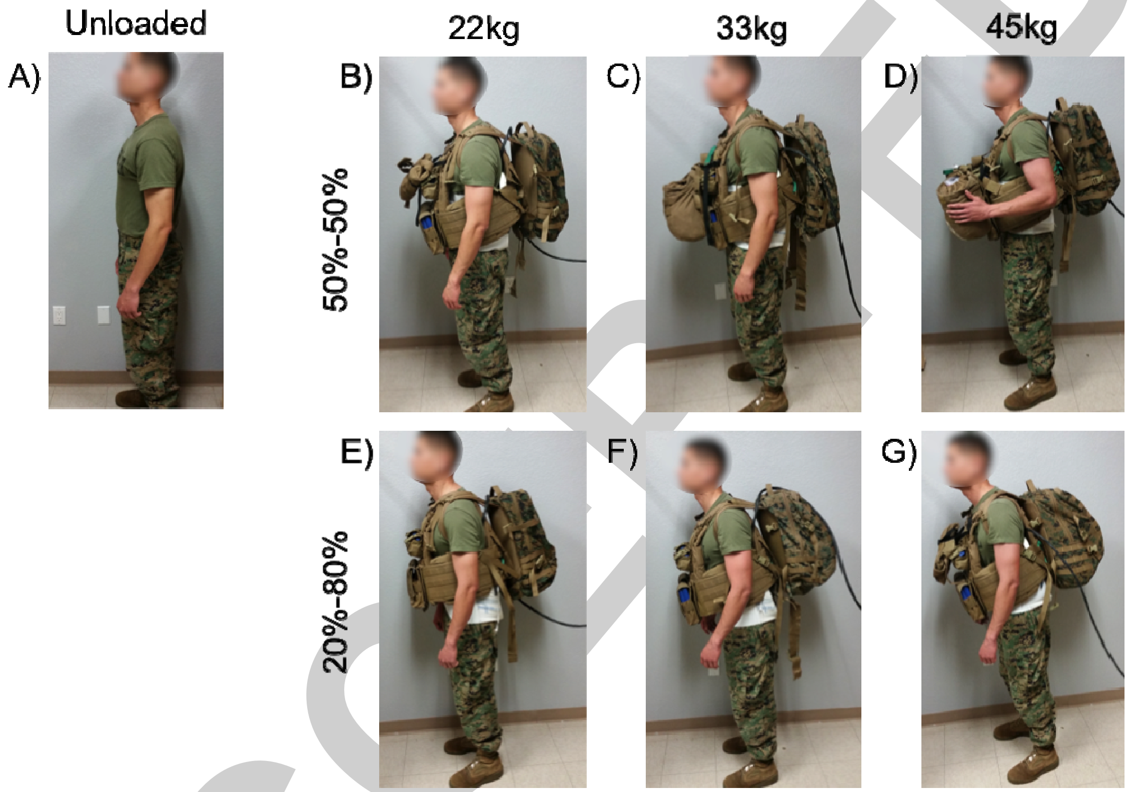


Figure 2 – A) Representative image showing footprints acquired using pressure mat (solid rectangle) indicating minimum bounding box (MBB, dashed rectangle). The center of pressure (CoP) trajectory is shown in red. Red circle indicates the average location of the CoP. B) Plot of the location of the CoP as a percentage of the width and height of the MBB. No differences were found across load magnitudes and distributions.

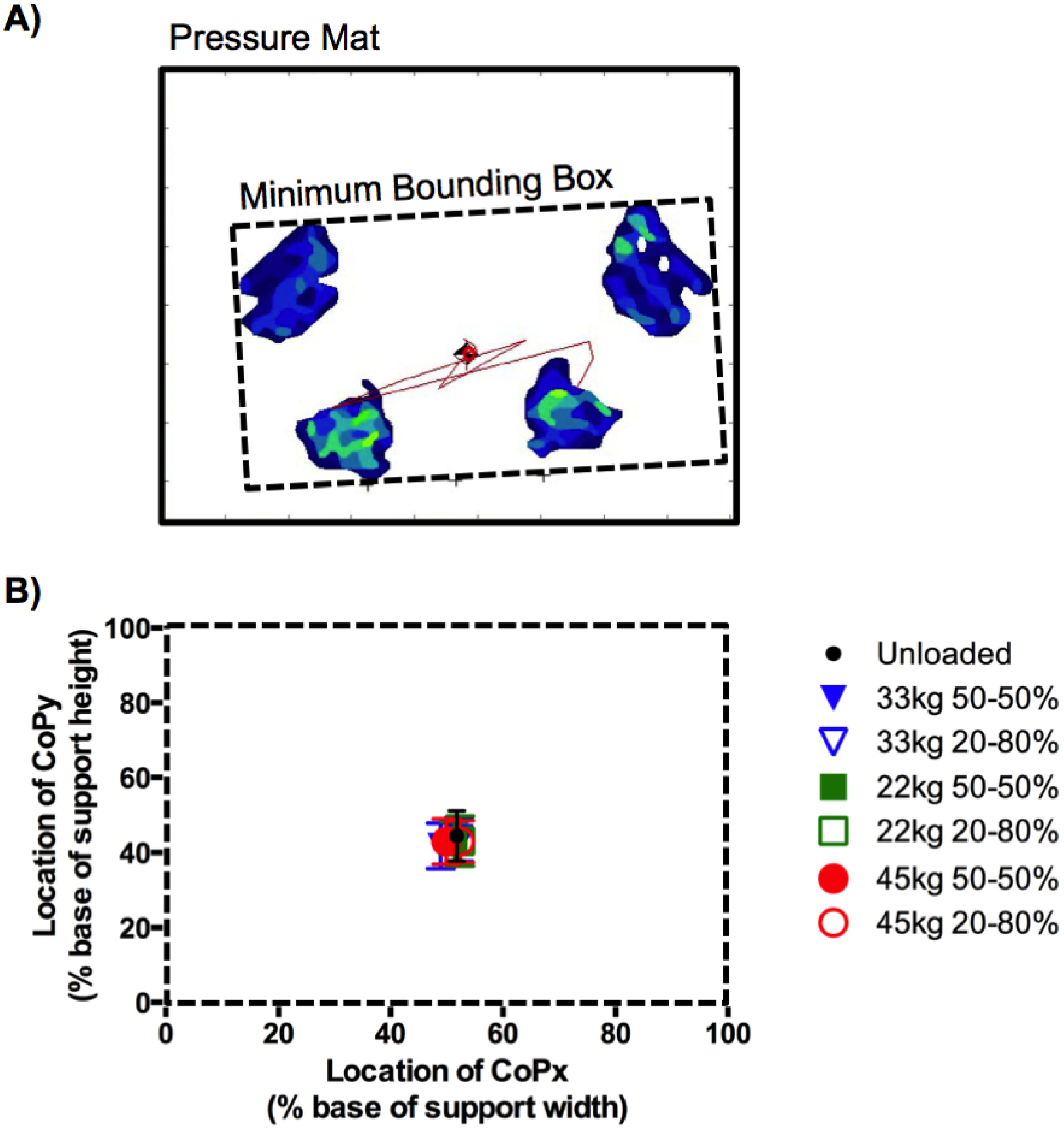


Figure 3 – Lumbar spine flexion results for loads carried with equal anterior-posterior distribution (clear bars) and with posterior bias (solid bars) for 22kg (clear grey), 33kg (dark grey) and 45kg (black). The dashed line represents trunk flexion when standing without external load. Solid horizontal bars represent significant differences (p<0.05) between load magnitudes and distributions. Asterisks represent significant differences when compared to the standing unloaded position.

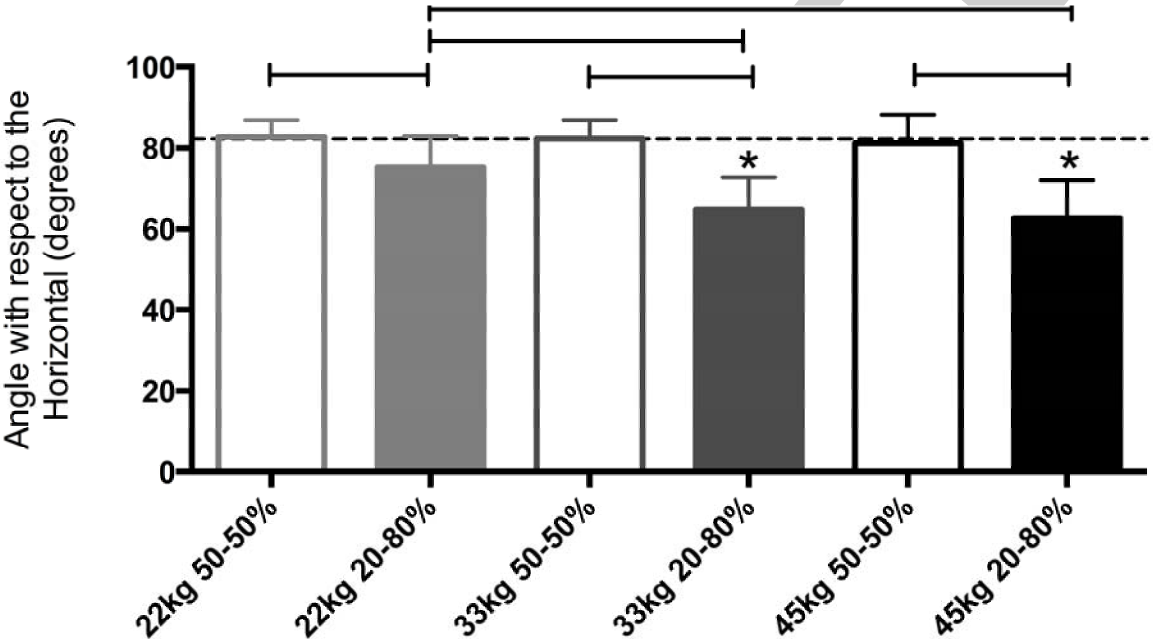


Figure 4 – Sacral orientation results for loads carried with equal anterior-posterior distribution (clear bars) and with posterior bias (solid bars) for 22kg (clear grey), 33kg (dark grey) and 45kg (black). The dashed line represents sacral orientation when standing without external load. Solid horizontal bars represent significant differences (p<0.05) between load magnitudes and distributions. Asterisks represent significant differences when compared to the standing unloaded position.

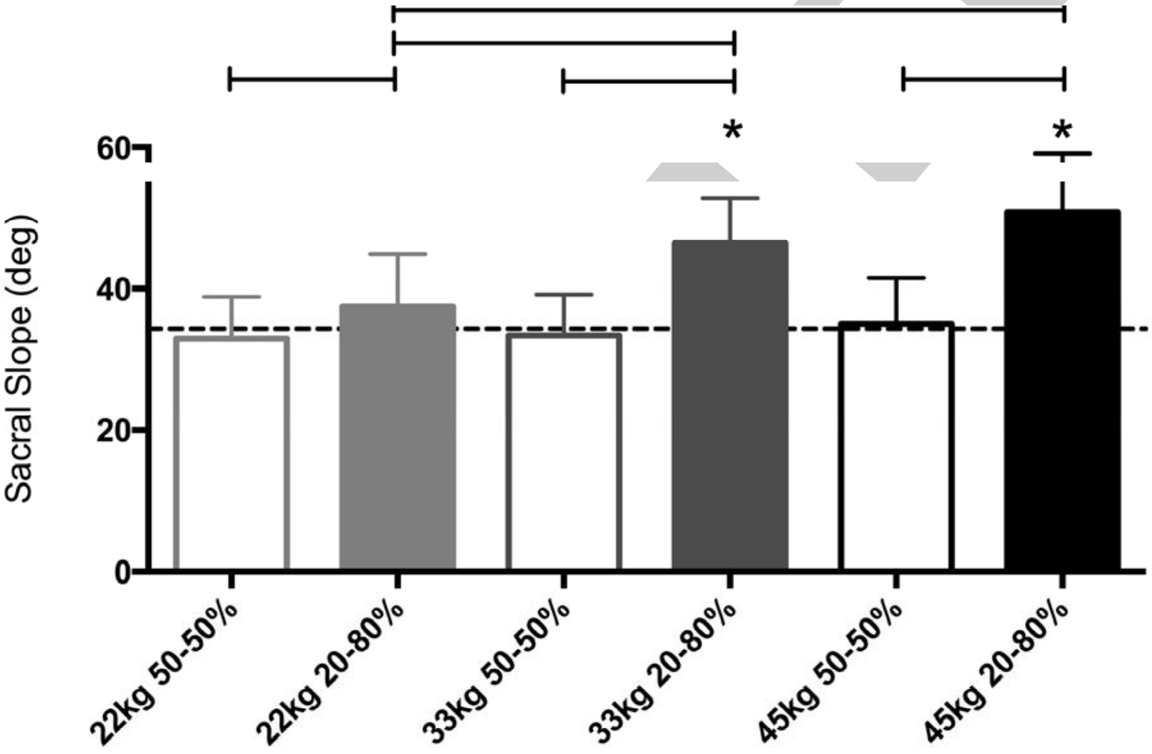
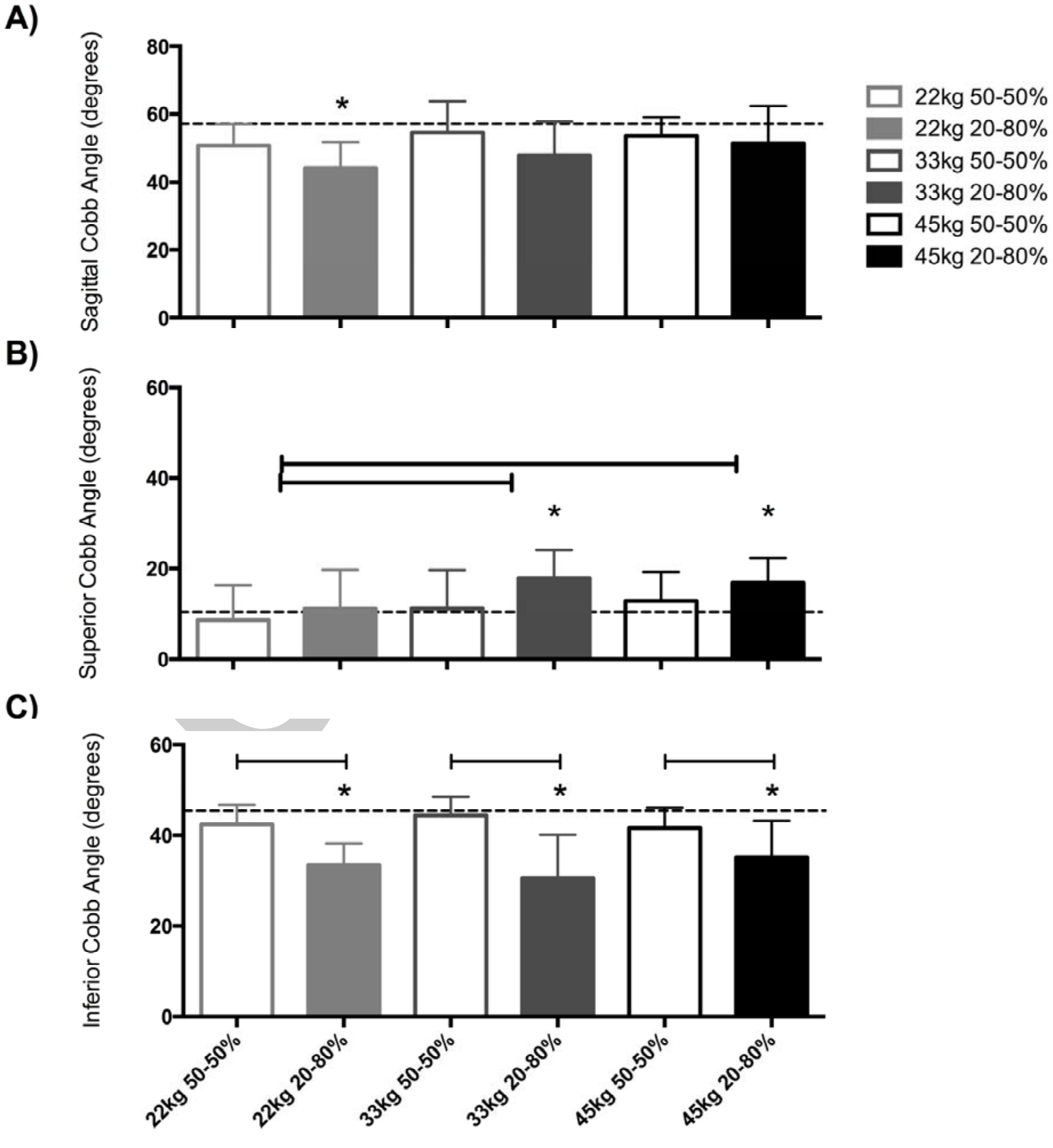
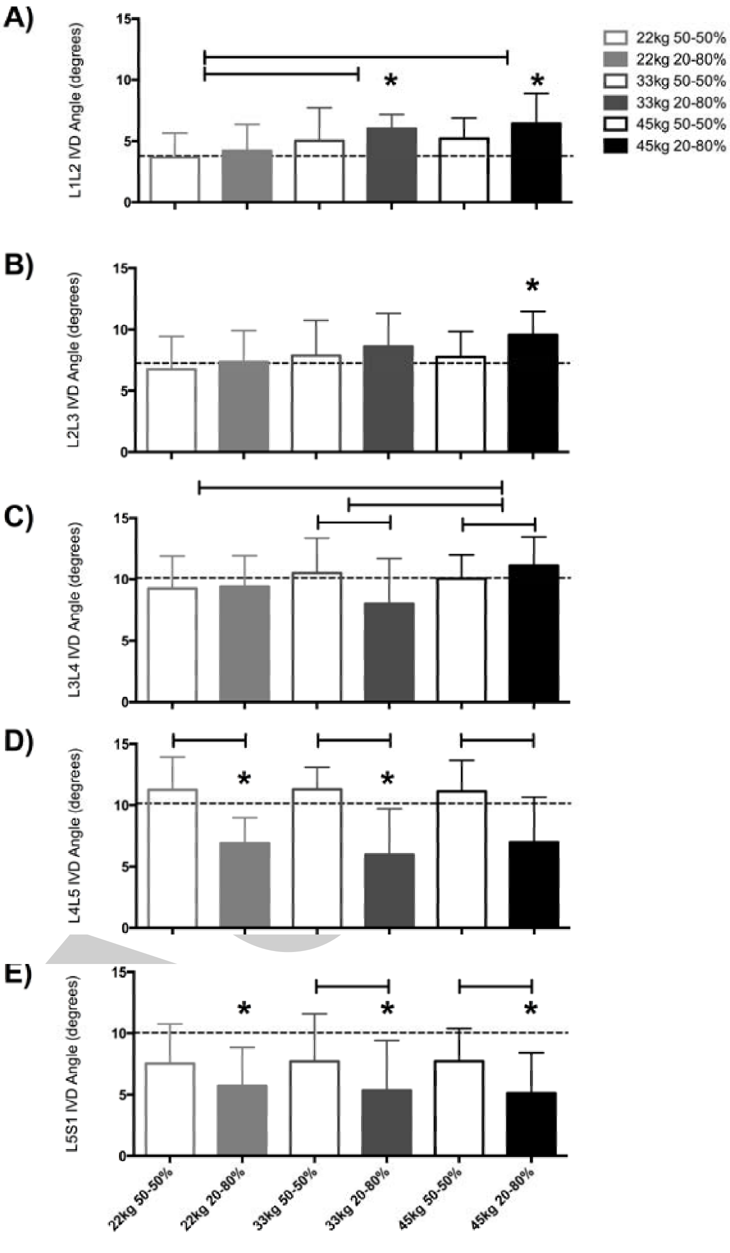


Figure 5 – A) Whole, B) superior, and C) inferior lumbar lordosis results for loads carried with equal anterior-posterior distribution (clear bars) and with posterior bias (solid bars) for 22kg (clear grey), 33kg (dark grey) and 45kg (black). The dashed line represents lordosis when standing without external load. Solid horizontal bars represent significant differences (p<0.05) between load magnitudes and distributions. Asterisks represent significant differences when compared to the standing unloaded position.



Supplement Figure 1 – Lumbar lordosis results at A) L1-L2, B) L2-L3, C) L3-L4, D) L4-L5 and E) L5-S1 for loads carried with equal anterior-posterior distribution (clear bars) and with posterior bias (solid bars) for 22kg (clear grey), 33kg (dark grey) and 45kg (black). The dashed line represents lordosis when standing without external load. Solid horizontal bars represent significant differences (p<0.05) between load magnitudes and distributions. Asterisks represent significant differences when compared to the standing unloaded position.



Supplement Figure 2 – Anterior (A-E), central (F-J), and posterior (K-O) intervertebral distances at L1-L2, L2-L3, L3-L4, L4-5 and L5-S1 (from top to bottom) for loads carried with equal anterior-posterior distribution (clear bars) and with posterior bias (solid bars) for 22kg (clear grey), 33kg (dark grey) and 45kg (black). The dashed line represents lordosis when standing without external load. Solid horizontal bars represent significant differences ($p<0.05$) between load magnitudes and distributions. Asterisks represent significant differences when compared to the standing unloaded position.