

Load spatial pathway and spine loading: how does lift origin and destination influence low back response?

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While heavy lifting has been identified as an important risk factor for low back disorders, little is known about workplace spatial layout – the relative positions of shelves and the impact of this on spine loads. The objective of the current study was to investigate how the relative positions of the load origin and destination impact three-dimensional spine loads. Seven females and seven males lifted an 11.4 kg box from an origin shelf to a destination shelf, each defined by height (elbow, knee and shoulder level) and asymmetry (60° clockwise, sagittally symmetric, 60° counter-clockwise) while their spine loading was assessed by an electromyographic-assisted model. The results indicated that the starting and destination heights and starting task asymmetry all had significant impact on spine compression (with an increase of between 400 and 1900 N when compared to the most neutral position) and lateral shear (with a 100 to 150 N increase) while the destination height impacted the anterior–posterior shear forces (with up to 400 N increase). The results of the current study emphasize the importance of proper workplace spatial layout, specifically the importance of specifying starting position of the load relative to the destination. Adjustment of the starting position will impact the three-dimensional spine loads while the destination height and asymmetry influence the shear forces. Furthermore, the influence of the specific pathway (origin relative to destination) indicates there may be a potential preparatory muscle response leading to the loads on the spine. Thus, the pathway of the box plays an important role in the spine responses during lifting, in that longer and non-neutral pathways increase spine loads – indicating the importance of the relative position of the origin and destination shelf.

Keywords: Lifting; Manual material handling; Trunk motion; Muscle recruitment strategy

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1. Introduction

As the cost of health care continues to increase, it has become more important to quantify the effect of workplace redesign upon spine loading during lifting. While the impact of weight lifted on spine loading has been extensively studied (Drury *et al.* 1989, Jager and Luttmann 1989, 1992, Marras and Sommerich 1991b, de Looze *et al.* 1996, Marras *et al.* 1997, Davis *et al.* 1998a, Fathallah *et al.* 1998, Granata *et al.* 1999, Marras *et al.* 1999b), few investigations have attempted to understand the importance of workplace spatial layout on the biomechanical response during lifting.

While many epidemiological studies have indicated that awkward static postures such as forward flexion (Punnett *et al.* 1991, Marras *et al.* 1993, 1995, Ono *et al.* 1997, Brulin *et al.* 1998, Josephson and Vingard 1998, Wickstrom and Pentti 1998, Hoogendoorn *et al.* 1999, Vingard *et al.* 2000, Ozguler *et al.* 2002) or flexion with twist or lateral flexion (Punnett *et al.* 1991, Bovenzi and Zadini 1992, Bovenzi and Betta 1994, Brulin *et al.* 1998, Wickstrom and Pentti 1998) increase the risk of low back pain, few field studies have investigated the dynamic relationship between workplace spatial layout and low back pain (Hughes *et al.* 1997). Several workplace layout design factors might directly impact the postures adopted during lifting. For example, lower lifting origin heights (e.g. closer to the floor) would increase the trunk flexion (Marras *et al.* 1997, 2001a, 2003) while asymmetry at the origin would increase the twist and lateral flexion motions (Ferguson *et al.* 1992, Allread *et al.* 1996). Thus, the position of the load lifted prior to lifting might contribute to the motions adopted by the individual. Theoretically, as the position of the load approaches the floor, the individual must flex further forward, producing more trunk moments as a result, and thus spine loads increase. Other researchers have found non-sagittal trunk moments to increase with more asymmetric postures (Gagnon and Gagnon 1992, Kingma *et al.* 1998).

These trunk postures could also influence spine loading. Laboratory studies (Marras *et al.* 1997, 2001a, 2003) have reported increased three-dimensional spine loads when lifting from low-level origin heights (knee level or below). In addition, origin asymmetry has been found to impact the loads on the spine. As the lift origin becomes more asymmetric, the complex spine loads increase compared to a sagittal symmetric origin (Marras and Sommerich 1991b, Jager and Luttmann 1992, Granata and Marras 1993, Fathallah *et al.* 1998, Marras and Davis 1998, Granata *et al.* 1999). Two studies (Marras and Sommerich 1991b, Marras and Davis 1998) reported increases in compression and lateral shear forces but decreases in anterior-posterior (A-P) shear forces when comparing asymmetric postures to a sagittally symmetric (sag sym) posture. Complex loading in the form of compression and shear forces was particularly intense for asymmetric lifts with greater weights and high lift rates (Davis and Marras 2000b). Additionally, the direction of the asymmetry at the origin of the dynamic lift has also been observed to influence the magnitude of the loads on the spine with greater loading during lifting from the counter-clockwise direction as a result of trunk kinematics and muscle activation (Marras and Davis 1998). However, the impact of spatial load origin path has never been investigated in a systematic manner.

Even less spine loading research has been reported on the impact of the load destination position. One study investigated destination height (Davis *et al.* 1998b) where individuals placed loads of different weight at known positions on a pallet. The spine loading increased as the height of the destination position decreased. No studies have been reported that evaluate task asymmetry at the destination.

Thus, there is a need to systematically evaluate how the load spatial pathway (the relative positions of the origin and destination locations) influences the three-dimensional

spine loads. The objective of this study was to quantify the spine loads (based on trunk kinematics, trunk kinetics and muscle coactivity) during lifting tasks where a load was moved from one position to another, where these vary in terms of height and task asymmetry. Origin and destination may impact muscle activity recruitment before the lift occurs, which will affect spine loading. Thus, it is important to understand how load location and motion path could influence spine loading throughout a lift.

2. Methods

2.1. Experimental design

The participants lifted an 11.4 kg box from an origin position (shelf) to a second destination position (shelf) while standing stationary on a force plate (e.g. feet were not able to move during lifts). Subjects picked up the box from a predetermined origin shelf and placed it on a predetermined destination shelf, adopting a preferred pathway with no specific directions as to how to lift. All of the shelves were positioned at a horizontal distance of 50.8 cm from the centre of the box to the spine. Prior to the lift, the subject was provided with information about the origin position of the box (visually), where to lift the box (destination) and when to lift the box.

The independent variables were the factors that define the relative position of the origin and destination shelves: origin height; origin asymmetry; destination height; and destination asymmetry. Three heights were used for both the origin and destination position (shoulder, elbow and knee height), which were adjusted to the specific dimensions of the subjects. Three asymmetries (relative to the sagittal plane) for the origin and destination shelves were also investigated (60° counter-clockwise, sag sym and 60° clockwise). All combinations of origin and destination positions were tested, yielding nine positions of the origin shelf and nine positions of the destination shelf, for a total of 81 lifts.

The dependent variables were the peak three-dimensional spine loads (compression, lateral shear and A–P shear). The peak three-dimensional spinal loads at the intervertebral joint L₅/S₁ were determined using the Ohio State University electromyographic (EMG)-assisted model developed over the last 20 years in the Biodynamics Laboratory (Marras and Sommerich 1991a,b, Granata and Marras 1993, Marras and Granata 1995, Fathallah *et al.* 1998, Marras *et al.* 1999a, 2001b, 2002, Jorgensen *et al.* 2001).

2.2. Subjects

A total of 14 subjects (seven males and seven females) participated in the study. All subjects were asymptomatic for low back pain at the time of the study and had no symptoms in the previous year or low back surgery. The subjects were inexperienced lifters and inexperienced in manual material handling tasks. Table 1 provides anthropometric measurements for both the male and female subjects.

2.3. Apparatus

The lumbar motion monitor (LMM) measured the trunk motion characteristics during the lifting tasks. The LMM is essentially an exoskeleton of the spine in the form of a triaxial electro-goniometer that measures the instantaneous three-dimensional position,

Table 1. Details of the participants (mean and standard deviation)

	Males (n = 7)	Females (n = 7)
Age (years)	22.4 (1.0)	22.4 (1.8)
Height (cm)	180.7 (9.0)	161.3 (6.6)
Weight (kg)	75.0 (10.3)	56.7 (8.4)
Shoulder height (cm)	147.9 (7.0)	132.4 (5.7)
Elbow height (cm)	109.8 (6.6)	98.2 (4.2)
Knee height (cm)	56.5 (5.7)	48.9 (3.7)

velocity and acceleration. More detail about the design, accuracy and application of the LMM can be found in Marras *et al.* (1992).

EMG activity was collected from the five pairs of trunk muscles through the use of bipolar silver-silver chloride surface electrodes spaced approximately 3 cm apart. The muscles being sampled were the right and left pairs of latissimus dorsi, erector spinae, rectus abdominus, external obliques and internal obliques using the standard placements described in Mirka and Marras (1993). The EMG signals were pre-amplified, high-pass filtered at 30 Hz, low-pass filtered at 1000 Hz, rectified and integrated via a 20 ms sliding window hardware filter.

A force plate and set of electrogoniometers was used to accurately estimate the moments supported by the trunk during the lifts. The electrogoniometers assessed the position of L5/S1 relative to the centre of the force plate as well as measuring the pelvic/hip orientation. The force and moments measured at the centre of the force plate were then translated and rotated to L5/S1 by the method developed by Fathallah *et al.* (1997).

2.4. Procedure

Upon arrival at the Biodynamics Laboratory, the subjects were briefed about the lifting tasks that were to be performed and then read and signed a consent form approved by the University's Institutional Review Board. Next, the five pairs of surface electrodes were applied to the subject using standard EMG techniques (National Institute for Occupational Safety and Health 1991). The skin impedances were kept under 500 K Ω ; to ensure high quality EMG signals. The subjects were then placed in a rigid structure where maximum isometric exertions were performed. These standard maximal exertions were used for normalization of the EMG data (as described in Marras and Mirka 1993) and included: extension at 20° of flexion; flexion in the upright posture; right and left lateral flexion in the upright posture; and right and left twisting in the upright posture. Upon completion of the maximal exertions, the subject was fitted with a LMM and positioned on the force plate where the electrogoniometric system used to track L5/S1 was attached. The subjects then completed the experimental conditions – lifting boxes from all combinations of origin and destination shelf positions (in random order).

2.5. Data processing and statistical analyses

Customized software converted the voltages recorded from the LMM into trunk angles, velocities and accelerations. The EMG activities for each of the muscles were normalized to the values obtained during the six maximal exertions. Normalized EMG, kinematic and kinetic data were inputted into the EMG-assisted model to obtain the predicted trunk

moments and spinal loads. Maximum (peak magnitude) values were determined for all the responses and spinal load variables. Descriptive statistics of all the dependent variables (three-dimensional spine loads) were determined as a function of the independent variables. A repeated-measures split-plot ANOVA was performed for all the dependent variables, with all significant effects being further analysed using Tukey multiple pairwise comparisons using the SAS statistical package. Finally, two separate follow-up regression analyses were performed to predict spinal loads: 1) using workplace characteristics – height and asymmetry of the origin and destination positions; and 2) using the relative positions of the origin and destination positions (for example, height expressed as function of stature of the individual subject). The first regression analysis provided the relative effect of the individual and two-factor interactions on each of the three-dimensional spine loads while the second regression analysis yielded equations that could be used to predict the three-dimensional spine loads when lifting for given origin and destination positions.

3. Results

3.1. Height and asymmetry main effects

Origin height, origin asymmetry, destination height and destination asymmetry each had a significant impact on the spine loads. The origin height and destination height each influenced the three-dimensional spine loads ($p < 0.0001$) while asymmetry (at origin and destination) impacted lateral shear and compression forces ($p < 0.005$) (see table 2). Lifting from knee height produced the largest compression force, followed by lifting from shoulder height, and the lowest compression forces occurred when lifting from elbow height. Lifting from the knee height shelf produced the greatest spine loads in all three planes. For the destination heights, lateral shear was greatest for the shoulder and knee heights while A–P shear was greatest at shoulder height. As with origin height, compression force was greatest at knee height (about 1680 N more than at elbow height). Thus, elbow height produced the lowest loads on the spine.

Asymmetry also impacted the compression ($p = 0.0001$) and lateral shear loads ($p = 0.005$). An increase of 60° of asymmetry of origin resulted in an increase of approximately 75 N in lateral shear and in A–P shear force as compared to the sag sym condition. Task asymmetry also increased the compressive forces, with greater increases occurring when lifting from a clockwise (to the right) origin (about 500 N) compared to a counter-clockwise origin. The clockwise destination shelf produced greater lateral shear (an increase of about 40 N) and compression (more than a 200 N increase) than the sag sym and counter-clockwise destination shelves.

3.2. Lift origin height by origin asymmetry interaction

As seen in figure 1, the position of the lift origin (as defined by both the height as well as asymmetry) had significant impact on the three-dimensional loads ($p < 0.001$). The lateral shear forces were impacted most for the asymmetric origin at the knee height (between 180 and 220 N increase over the sagittal symmetric knee height). While there was limited impact of the origin position on the A–P shear forces, increases were seen at the asymmetric, knee height origins (about 150 N increase). Lifting from all three of the origin shelves at knee height increased the compressive forces but larger increases were seen for the asymmetric origins (with between 1500 N and 2200 N increases over elbow and shoulder heights).

Table 2. Peak three-dimensional spine loads as a function of origin asymmetry, origin height, destination asymmetry, and destination height (main effects)

	Shoulder height		Elbow height		Knee height	
	Mean	SD	Mean	SD	Mean	SD
Origin height						
Lateral shear (N)	237.5 ^A	215.5	220.8 ^A	206.3	395.5 ^B	325.2
Anterior-Posterior shear (N)	1033.6 ^B	391.0	947.1 ^A	446.1	1089.7 ^C	558.5
Compression (N)	4036.8 ^A	2016.5	4004.1 ^A	2050.8	5923.5 ^B	2462.3
	Shoulder height		Elbow height		Knee height	
Destination height	Mean	SD	Mean	SD	Mean	SD
Lateral shear (N)	302.8 ^B	286.4	229.2 ^A	208.1	322.3 ^B	288.8
Anterior-Posterior shear (N)	1288.7 ^C	491.2	920.4 ^B	332.8	861.6 ^A	465.1
Compression (N)	4254.8 ^B	2169.6	4016.8 ^A	1935.0	5697.7 ^C	2579.8
	60° CCW		Sagittal Symmetric		60° CW	
Origin asymmetry	Mean	SD	Mean	SD	Mean	SD
Lateral shear (N)	307.3 ^B	312.2	232.0 ^A	227.1	315.0 ^B	245.3
Anterior-Posterior shear (N)	1039.0 ^A	506.4	1000.2 ^A	422.4	1031.1 ^A	488.9
Compression (N)	4794.1 ^B	2572.1	4340.4 ^A	2069.2	4834.1 ^B	2390.6
	60° CCW		Sagittal Symmetric		60° CW	
Destination asymmetry	Mean	SD	Mean	SD	Mean	SD
Lateral shear (N)	275.5 ^A	263.2	263.2 ^A	274.4	315.4 ^B	257.6
Anterior-Posterior shear (N)	1024.2 ^A	476.9	1007.6 ^A	454.4	1038.7 ^A	490.1
Compression (N)	4662.1 ^B	2291.7	4434.7 ^A	2127.9	4871.4 ^C	2624.8

Different superscript alphanumeric characters indicate a statistically significant difference, across a given row, for example, a value with an 'A' is different from a value with a 'B'. CCW = counter-clockwise; CW = clockwise.

3.3. Destination height by destination asymmetry interaction

The destination position (defined by its asymmetry and height) also affected the three-dimensional spine loads (figure 2) ($p < 0.0003$). In terms of lateral shear, an increase was observed when lifting from the shoulder and knee heights as compared to elbow height. Task asymmetry at the destination was particularly unfavourable at knee height. Differences in A–P shear force were noted between the asymmetric and sag sym position at knee height with the largest A–P shear loads occurring in the shoulder destination conditions (about 340 to 550 N higher than elbow and knee height). Compressive loads were the greatest in the knee height destination condition with modest increases in the asymmetric positions (680 N to 1100 N).

3.4. Origin height by destination height interaction

Another important interaction that significantly impacted the three-dimensional spine loads was the relative height difference between the origin and destination (figure 3) ($p < 0.0001$). Lateral shear forces were greatest when the lift origin was at knee height and the combination of lifting from knee height combined with a destination at shoulder height. The A–P shear loads were the highest when destination height was at the shoulder, in particular, greatest when lifting from knee to shoulder height. Compression forces were highest when the origin or destination height was at knee level with loads above 5400 N.

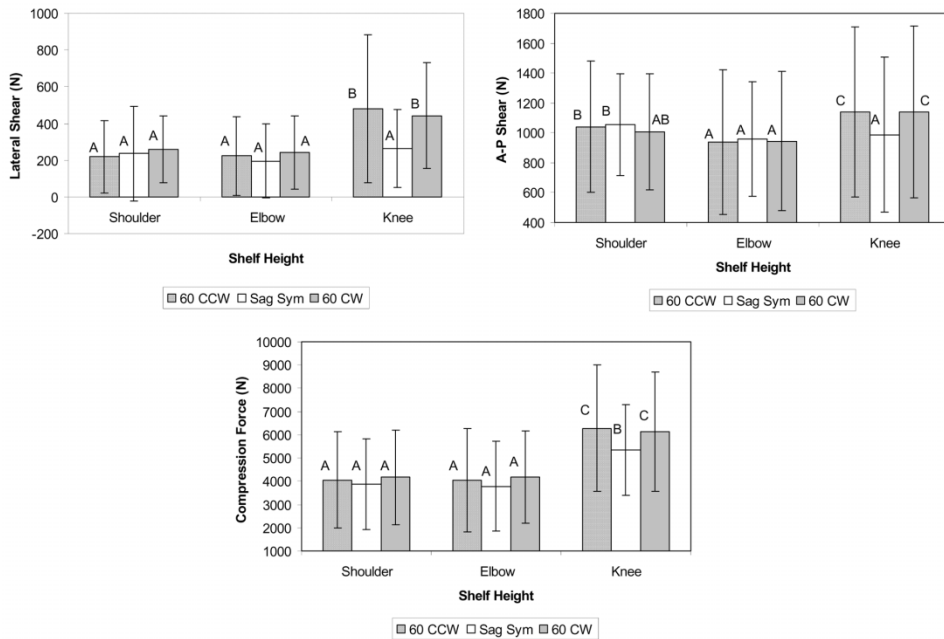


Figure 1. Impact of origin position on the peak three-dimensional spine loads. (Different superscript alphanumeric characters indicate a statistically significant difference, across a given row, for example, a value with an 'A' is different from a value with a 'B'). A-P = anterior-posterior; 60 CCW = 60° counter-clockwise; Sag Sym = sagittally symmetric; 60 CW = 60° clockwise.

3.5. Load travel path

The actual path that the box travels as defined by the relative position of the origin and destination (as defined by asymmetry and height) also provides information as to where the three-dimensional loads increase. Figure 4 shows the percentage differences for all combinations of origin and destination shelves relative to the most neutral lift (lifting from elbow sagittal symmetric origin shelf to elbow sagittal symmetric destination shelf). As shown in figure 4, the lateral shear loads increased the most (based on percentage differences) due to the lower initial values as compared to A-P shear and compression forces. However, the more important aspect of this figure was the relative trend. For example, significant increases in compressive loads occur when lifting from or to knee height and even more when lifting to an asymmetric position. Also, lateral shear forces are more impacted by task asymmetry, particularly at knee level. Overall, this figure provides an overview of the expected impact on the three-dimensional loads when lifting from one shelf height to another as compared to the neutral lift.

3.6. Linear regression models

Table 3 provides equations that can be used to predict the three-dimensional spine loads based upon spatial origination of the load path. These regression equations would be most appropriate for lifting an 11.4 kg box at a comfortable lifting rate (preferred) and under similar conditions as the current study. While the regression equations were based

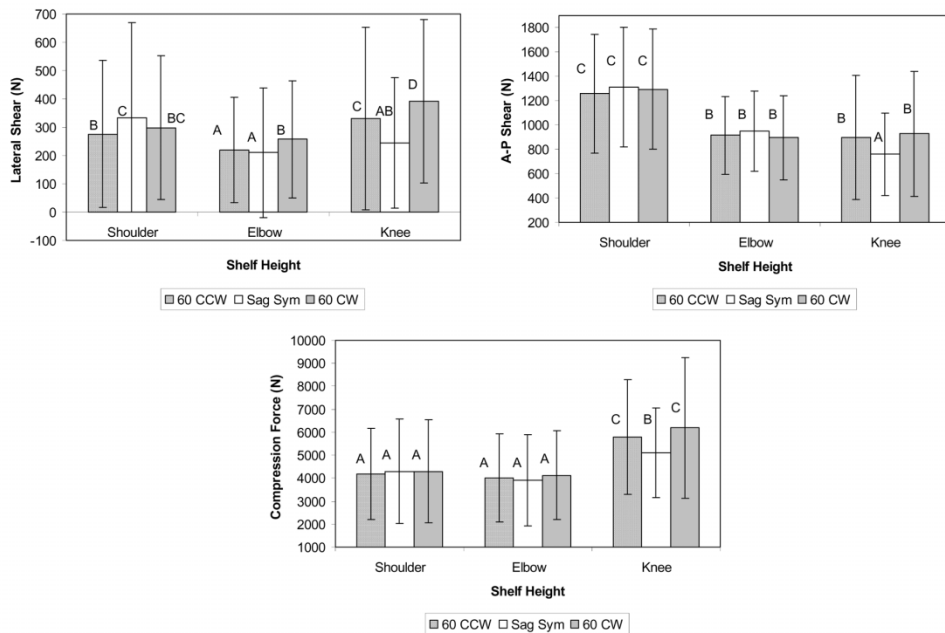


Figure 2. Impact of destination position on the peak three-dimensional spine loads. (Different superscript alphanumeric characters indicate a statistically significant difference, across a given row, for example, a value with an 'A' is different from a value with a 'B'). A-P = anterior-posterior; 60° CCW = 60° counter-clockwise; Sag Sym = sagittally symmetric; 60° CW = 60° clockwise.

on the three asymmetries at both the origin and destination, the regression equations will allow for extrapolation to other asymmetries by inputting other asymmetric positions into the equations (with clockwise being positive, counter-clockwise being negative and sagittal symmetric equal to zero). In order to use these equations, one must convert the origin and destination heights into percentage of overall standing height. For example, the predicted compression force for a person (stature = 1.70 m) lifting from a 30° clockwise asymmetric shelf at 60 cm height shelf (knee height with value of 0.3529 for origin height) to a 60° counter-clockwise asymmetric shelf at 115 cm (elbow height with value of 0.6765 for destination height) would be 4625 N.

4. Discussion

This study describes how the relative position of the origin and destination impacts the magnitude and nature of the loads on the spine. The study has gone beyond the traditional evaluation of lifting where the investigations concentrated on the initiation of the lift to the combination of the start and destination position. When considering origin and destination locations themselves, several important relationships become evident. First, the results clearly show that when lifting from lower origins dramatic increases in the lateral shear and compressive forces occur relative to the elbow height conditions. Second, more asymmetric origins produced modest increases in lateral shear and compression forces, with similar trends to those previously reported (Marras and Sommerich 1991b,

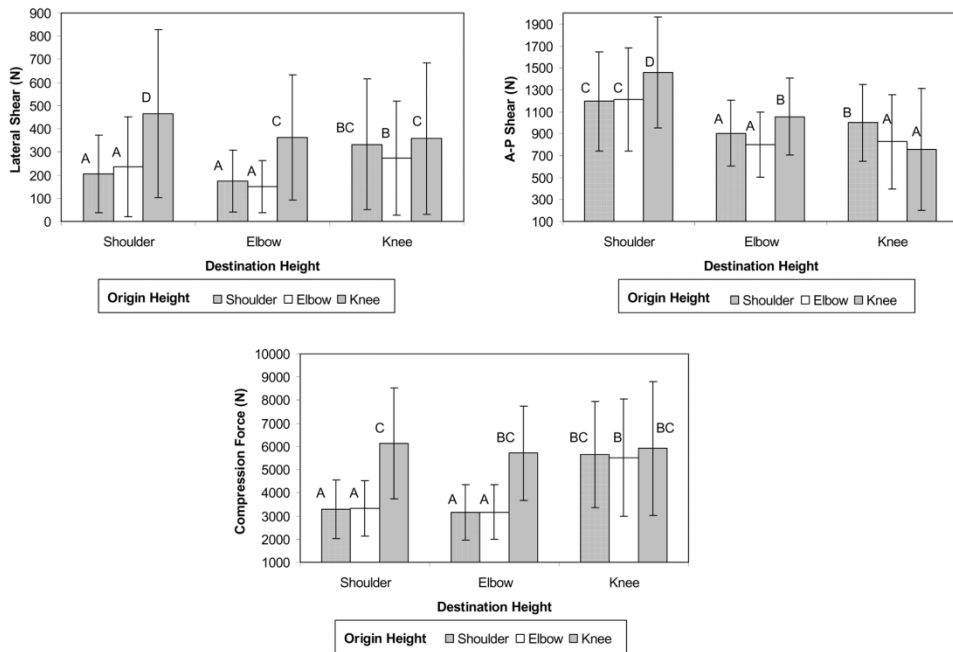


Figure 3. Impact of the relative height of the origin and destination positions on the peak three-dimensional spine loads. (Different superscript alphanumeric characters indicate a statistically significant difference, across a given row, for example, a value with an 'A' is different from a value with a 'B'). A-P = anterior-posterior.

Jager and Luttmann 1992, Granata and Marras 1993, Fathallah *et al.* 1998, Marras and Davis 1998, Granata *et al.* 1999). Third, the destination height increased the three-dimensional spine loads not only in the lower origins (knee height) but also the higher origins (shoulder) as compared to the elbow height origins. Fourth, a more asymmetric destination shelf increased the compressive loads on the spine, with the greatest magnitudes occurring in the clockwise direction, which was different than what has been previously reported (Marras and Davis 1998). These differences may have occurred from different muscle recruitment patterns that may have accompanied the adopted motions in the different experimental conditions. In the current study, the boxes were lifted from one shelf to another while the Marras and Davis' study had participants lifting from shelf to upright position (holding the box). In all, each of the individual workplace origin and destination location factors significantly contributes to the nature and magnitude of the loads. Thus, the results of the current study support the inclusion of three multipliers into the National Institute for Occupational Safety and Health (1991) lifting equation (Waters *et al.* 1993) – vertical height (lift origin height), task asymmetry and vertical travel distance (relative height of origin and destination). However, the results appear to suggest that the combinations of these factors are even more informative.

4.1. Combined effect of height and asymmetry on spine loads

The spatial orientation of the work is defined by the combination of two individual characteristics – lift height and task asymmetry rather than just height or asymmetry. As

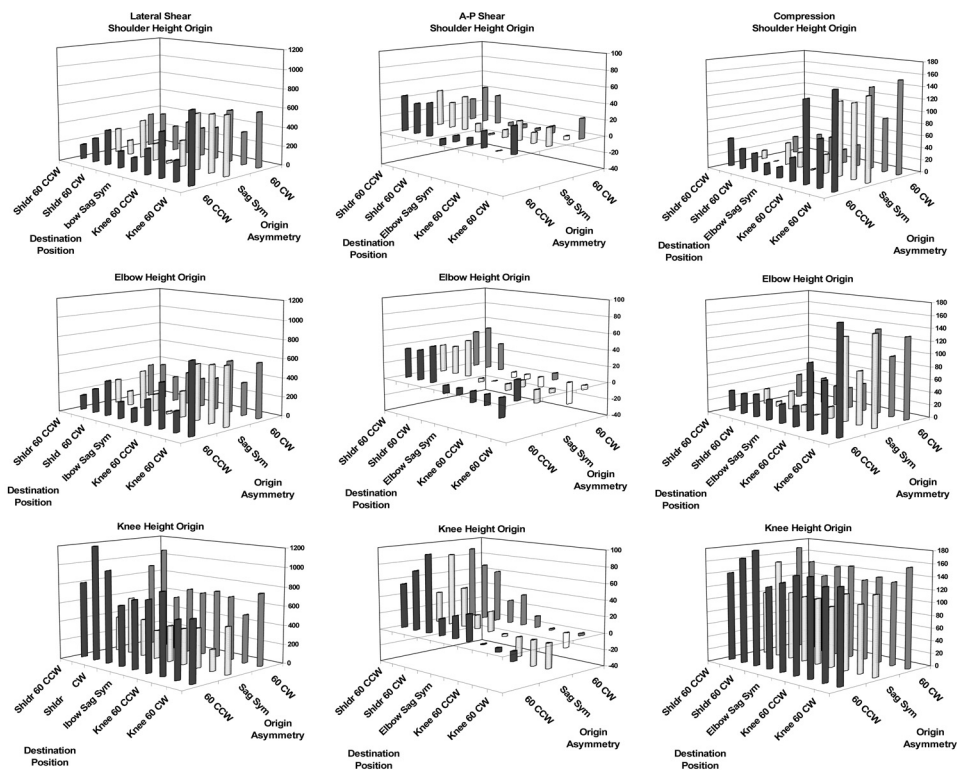


Figure 4. Peak three-dimensional spine loads as a function of pathway (as defined by the height and asymmetry of the origin relative to the destination). Notice different scales for each of the three-dimensional spinal loads (lateral shear—1200%, anterior-posterior (A-P) shear—200%, and compression—180% relative to the most neutral lift (lifting from elbow sagittal symmetric origin shelf to elbow sagittal symmetric destination shelf)). 60 CCW = 60° counter-clockwise; Sag Sym = sagittally symmetric; 60 CW = 60° clockwise.

seen in figures 1 and 2, there is an interactive effect between lift height and task asymmetry at both the origin and destination. In general, the combination of lower height and greater asymmetry produced the highest three-dimensional spine loads, especially for the lift origin. In practical terms, this means that workers would be at greater risk of low back injury when lifting from low asymmetric heights and improvements can be beneficially implemented at either the origin or destination (and preferably both). These two figures (1 and 2) also indicate the importance of good ergonomics. The best lifting conditions were lifting to and from sag sym shelves at elbow height.

The relative position of the origin and destination also had a significant impact on the spine loads with greater differences in heights resulting in higher magnitudes of loads. Lifting the box from knee height to shoulder height produced the highest loads in all three planes. These results provide some evidence to support the vertical travel multiplier in the National Institute for Occupational Safety and Health (1991) lifting equation (Waters *et al.* 1993), especially when considering A–P shear force, which significantly

Table 3. Regression equation to predict peak three-dimensional spine loads for the workplace parameters – origin height (OH), origin asymmetry (OA), destination height (DH), destination asymmetry (DA) and two-way interactions when lifting an 11.4 kg box (where origin and destination heights are converted as a percentage of the stature of the individual). Each regression equation was significant at $\alpha < 0.001$.

Spine load	Equation
Lateral shear	$166.46 - 0.873*OA + 0.172*DA + 2.448*OH + 5.141*DH - 0.00315*OA*DA + 0.00846*DA*OH - 0.09578*OH*DH + 0.0121*OA*OH + 0.0059*OA*DH - 0.00576*DA*DH - 0.0000079*OH*OA*DH*DA$
Anterior-Posterior shear	$7.32 + 0.063*OA - 0.412*DA + 9.481*OH + 18.721*DH - 0.01006*OA*DA + 0.00946*DA*OH - 0.18386*OH*DH - 0.00617*OA*OH + 0.00763*OA*DH - 0.00019*DA*DH - 0.0000015*OH*OA*DH*DA$
Compression	$4709.39 - 1.181*OA + 2.281*DA + 25.905*OH + 34.684*DH - 0.03*OA*DA + 0.03782*DA*OH - 1.06245*OH*DH + 0.03972*OA*OH - 0.00112*OA*DH - 0.04816*DA*DH - 0.00000549*OH*OA*DH*DA$

increased with greater vertical travel distances (e.g. larger difference between origin and destination shelf heights). A more in-depth evaluation of the pathway (as seen in figure 4) yields even more complexity in the nature of the loads. The loads that are imposed upon the spine are not simply dependent upon the load origin or destination heights or task asymmetries, independently, but rather on their relative spatial position as defined by the relative combination of both height and asymmetry of the lift origin and destination. Thus, the findings of this study suggest that longer pathways, such as lifting from an asymmetric knee height origin to an asymmetric shoulder height destination, produce the largest and most complex spine loads (high compression and shear). However, Gagnon *et al.* (1996) found that the negative effects of long asymmetric lifting pathways can be minimized through the use of a pivoting of the hips during the lift, although the asymmetries were greater than those evaluated in the current study.

4.2. Relevance of workplace layout characteristics

These results indicate that many of the workplace factors that relate to load position have a significant role in determining the loads on the spine. One question still remains about what is the most important factor for each of the spine loads. In order to answer this question, the relative percentage of the explained variance in each of the spine loads was determined by computing the partial r-square values for the main effects and interaction terms for the shelf parameters. Figure 5 shows the relative contribution of each of the factors for lateral shear, A–P shear and compression force variance. Origin height was the major contributor for both lateral shear and compression, indicating that alteration of this factor would have the greatest impact on these loads. Other factors such as origin asymmetry, relative heights of origin and destination, and combination of origin height and destination asymmetry significantly contributed to the lateral shear forces. Destination height and the relative difference in height of the load origin and destination also contributed significantly to compression. The largest contributor to A–P shear forces was the height of the destination, followed by the relative heights of the origin and destination. Thus, variables relating to load height dominated compression and A–P shear, whilst the combination of height and asymmetry influenced the lateral shear forces. These results provide a starting point for determining which aspects of the workplace would yield the greatest benefit in reducing the risk of low back injuries.

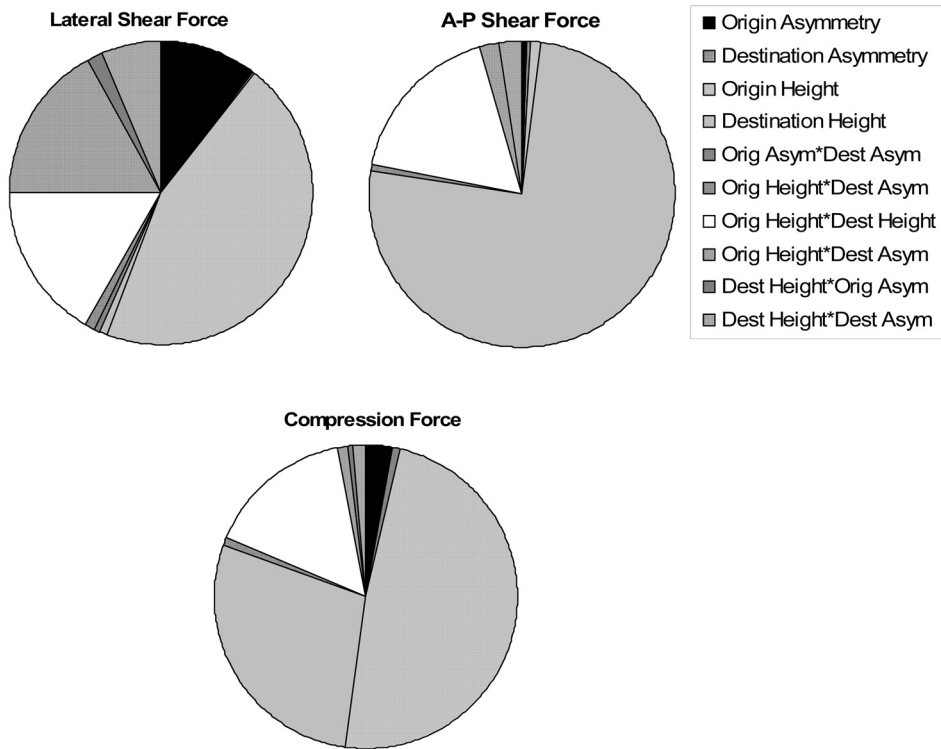


Figure 5. Relative contribution of the workplace layout characteristics for each of the peak three-dimensional spine loads (as predicted by the partial r^2). A-P = anterior-posterior.

4.3. Predicting spine loads from workplace layout factors

Table 3 provided three regression equations that would predict three-dimensional spine loads under very specific (limited) conditions – lifting weights of 11.4 kg at a comfortable lift rate and feet remaining stationary. The utility of these equations is the ability to determine how the magnitudes of the spine loads change when lifting between two different shelf positions. The equations allow one to gain an appreciation of how other asymmetries and shelf heights may influence the spine loads by allowing for extrapolation and interpolation. Caution must be used in applying these equations to the lifting of heavier or lighter boxes, since there is no way of knowing how weight impacts the loads relative to the other factors, based on the current study's results. Future studies could build on these equations by adding other weights and factors to gain a better appreciation of how workplace factors contribute to spine loads, particularly the three-dimensional load components.

4.4. Muscle recruitment strategy

The results of the study also point to a potential underlying muscle recruitment strategy that drives the spine load response to a specific lift pathway. With the nature and

magnitude of the spine loads depending not only upon the origin but also upon the destination, individuals appear to initiate a motor controller that drives the motion and load response. In other words, spine loads were impacted by not only the position of the origin shelf but also the relative position of the destination shelf. Thus, it appears that the motor controller predicts the pathway based on the combination of origin and destination and it is not sufficient to just know origin or destination exclusively. However, this preparatory response will need to be evaluated further to thoroughly understand the motor controller that drives the spine response. However, some evidence has been reported previously (Marras and Davis 1998) where the muscle activity during asymmetric lifting was dependent upon the asymmetric position of the origin shelf – with greater activity in both agonistic and antagonistic muscles for more asymmetric shelves.

4.5. Limitations of the study

In order to better appreciate the results of the study, several considerations need to be expanded upon. First, the feet of the individuals were required to remain stationary during the lifting tasks to ensure high quality of measurement of the trunk moments. However, this requirement may have influenced the motions adopted by the individuals as well as forced a specific horizontal moment arm (constant for all subjects and all conditions). As a result, the loads on the spine could be exaggerated in the sense of the absolute values but the trends and relative nature of the loads for the different lifting conditions would be preserved. Second, the study population was young and very fit, with relatively limited manual material handling experience. The responses for these individuals may be different from those of a more experienced, older or heavier population. Gagnon *et al.* (1996) reported that experienced material handlers and novices adopted significantly different lifting strategies with regard to leg (knee) motion, especially when able to move one foot during the lift. Experts had less knee motion than novices during asymmetric lifting. Thus, experience and the requirement of fixed positions for the feet may have impacted the spine loads produced under the current study's conditions. Furthermore, certain conditions, such as shoulder height shelves, may be exacerbated for weaker or unconditioned individuals. The point here is that one must consider the interaction between the worker and the workplace rather than just the workplace itself. Third, the shelf heights were adjusted to the anthropometry of the individual, representing a best-case scenario. In many circumstances in the workplace, there is limited adjustment, potentially having even greater impact on the spine loads for relative heights of the shelves. Fourth, the weight was held constant for all the conditions. Whilst weight was not targeted in the current study, it has been shown to significantly impact the loads on the spine (Davis and Marras 2000a) and may further complicate the relationship between the relative positions of the origin and destination shelves. A possible example of this would be that a heavier weight may magnify the loads when lifting from the knee height shelves, placing the worker at even more risk. Next, the investigation focused exclusively upon the lumbar spine loading. From an ergonomic perspective, there may be trade-offs in loading on other parts of the body (e.g. shoulders) that must be considered when optimizing workplace design. Fifth, the lifts were two-handed. Previous research has shown one-hand lifting to impact the significance of asymmetry with regard to spine loads (Marras and Davis 1998). Finally, the variation in shelf height and task asymmetry was limited (with three levels of height and two asymmetric positions). To gain a true appreciation of how shelf height and task asymmetry trade-off and impact the nature and magnitude of the spine loads, additional

levels would have to be investigated. Regions need to be identified to minimize the three-dimensional spine loads – resulting in answers for the following questions: how far away from elbow height is sufficient to increase the loads? are more asymmetric positions ($> 60^\circ$) more detrimental? and what is the proper lifting envelope that minimizes the loads? Answers to these questions will ultimately provide valuable information for the practitioner, who can then design the proper workplace layout to minimize the risk of low back injury.

5. Conclusion

Workplace factors that relate to the positions of the origin and destination have been found to be directly related to both the magnitude and the nature of the loads on the spine. In general, the heights of the shelves play a vital role in the loads produced during lifting, with origin height having the greatest impact on lateral shear and compression and destination height being the major contributor of A–P shear. However, the results of the study indicate that simple evaluations of the workplace that rely on single work measures (e.g. origin or destination position) provide only a partial picture of the risk of low back injury. In other words, the pathway or relative positions of the origin and destination drive the loads more than any single workplace factor (such as height or asymmetry independently). In all, this study provides evidence about the potential for ergonomic controls, such as changes to low or high shelf heights (e.g. at knee or shoulder level) and asymmetric positions, and suggests that measures should consider the entire pathway of motion during lifting. As previously reported, the loads on the spine are minimized when lifting from more neutral shelf positions. While previous studies have concentrated on lift origin positions, the current study also emphasizes the importance of well-thought-out destination location.

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