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Spine loading during asymmetric lifting using one versus two hands

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This study documented three-dimensional spinal loading associated with asymmetric lifting while using either one or two hands to perform the task. Lift asymmetry was defined as a function of the load origin relative to the sagittal plane of the body. Lifts occurred at 0, 30, or 60° off the sagittal plane on both sides of the body (lifting from the right and from the left relative to the sagittal plane). Ten subjects lifted a 13.7 kg box from one of these origins to a sagittally symmetric destination. Spinal loads were estimated through the use of a validated EMG-assisted model. Spine compression and lateral shear forces increased as the lift origin became more asymmetric. However, spinal compression and lateral shear increased by about twice the rate when lifting from origins to the left of the sagittal plane compared to lifting from origins to the right of the sagittal plane. Anterior-posterior spinal shear decreased as asymmetry increased with larger decreases occurring when lift origins occurred to the right of the sagittal plane. One-hand lifting changed the compression and shear profiles significantly. One-hand lifts using the hand on the same side of the body as the load resulted in compression forces that were approximately equal to those observed when lifting with two hands in a sagittally symmetric position. Anterior-posterior shear decreased and lateral shear increased under these conditions. These results reflect the trade-offs that must be considered among spinal forces during asymmetric lifting while using one or two hands. These findings have significant implications for task assessment interpretation and workplace design.

1. Introduction

It has been estimated that up to 85% of the workforce will suffer from a low-back disorder (LBD) sometime during their working lives (Spengler *et al.* 1986). Manual materials handling (MMH) tasks have been associated with the majority of these work-related LBDs (Snook *et al.* 1978, Bigos *et al.* 1986). MMH tasks can require the worker to lift, bend forward, bend laterally, twist, maintain static postures, carry heavy loads, or perform combinations of these activities (Snook *et al.* 1978, Andersson 1981, Kelsey *et al.* 1984, Bigos *et al.* 1986, Marras *et al.* 1993, 1995).

A commonly observed work condition in industry is that of lifting from asymmetric positions (Marras *et al.* 1993, 1995). Lift asymmetry has been associated with decreased trunk strength (Garg and Badger 1986, Marras and Mirka 1989, Ferguson *et al.* 1992), a reduction in the maximum acceptable weight of lift (Garg and Badger 1986, Mital and Fard 1986, Mital *et al.* 1989), and more complex trunk motions (Ferguson and Marras 1992, Ferguson *et al.* 1992, Allread *et al.* 1996).

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During asymmetric lifts, the support of the external load is shifted from the large erector spinae muscles to smaller, less capable oblique muscles (Marras and Mirka 1992). Increases in trunk muscle coactivity has also been associated with increased asymmetry and results in increased shear and compression loading on the spine (Marras and Sommerich 1991b, Granata and Marras 1993). Collectively, these findings suggest that lifting capacity is reduced and spinal loading may increase when lifting asymmetrically. However, the degree to which trunk loading is increased during asymmetric lifting and the relationship to workplace asymmetric lifting conditions has not been documented.

Most of the studies cited have investigated the effects of asymmetry as a function of asymmetric lift origins occurring to the right of the sagittal plane. Based upon these studies, lifting guides have been developed that discount the allowable weight of lift as a function of the degree of asymmetry associated with the lift. For example, the Revised NIOSH Lifting Equation (Waters *et al.* 1994) mediates lifting limits by about 10% for every 30° of asymmetry involved in the lift regardless of whether lift origins occur on the left or right side. Conventional logic assumed that trunk muscle response, spinal loading, and the subsequent risk associated with lifts from the right were mirror images of those lifts performed to the left. However, no studies have tested this hypothesis.

The biomechanical literature, on the other hand, implies that the loading on the spine might depend upon the direction of lift asymmetry (lifts from the left or right). McGill *et al.* (1988) found that the cross-sectional areas of the erector spinae, external oblique, and internal oblique muscles on the right-hand side of the body were 10 to 14% smaller than the corresponding left side muscles, whereas, the rectus abdominus muscles on the right-hand side of the body were 11% larger than the left side rectus abdominus muscles. Since these muscles generate internal reactive trunk moments that counteract the external momemt imposed by the load, one would expect that lifted loads would be supported differently depending on the side of the body that supports the loads. Recruitment of trunk muscles of varying cross-sectional area would be expected to result in different loading patterns on the spine.

Most lifting analysis methods assume that the worker uses both hands to lift an object. However, a common observation in industry is the occurrence of one-handed lifts. One would expect that this under-appreciated factor (number of hands used in the lift) would strongly interact with lift asymmetry to influence trunk muscle recruitment patterns, spinal loading, and risk of LBD. Workers often employ single-hand lifting techniques while performing lifts in confined spaces or poorly designed work areas (e.g. reaching into the back of a bin). One-hand lifting evaluations have been limited to assessing fatigue and maximum acceptable weights of lift (Garg and Saxena 1982, Garg 1983). Neither of these studies compared one-hand lifting to two-hand lifting. Allread and colleagues (1996) have been one of the few groups to compare one-hand and two-hand lifting situations in a controlled environment. This study focused upon trunk kinematic changes and found that one-hand lifting resulted in more sagittal flexion and lateral velocity but lower three-dimensional accelerations and twisting, as compared to two-hand lifting. An additional void exists in the body of knowledge in that we do not know how one-handed lifting affects spinal loading. None of these studies have investigated the spinal loads resulting from one-hand as compared to two-hand lifting. The Revised NIOSH Lifting Equation (Waters *et al.* 1994) specifically states that it does not apply to one-handed lifting. Yet, one would expect that significant trade-offs might exist between the number of hands used during a lift and the asymmetric conditions associated with the work.

Several biomechanical trade-offs could result when lifting with one-hand as compared to two-hands. Individuals may twist less during one-hand asymmetric lifting which may place the spine in a more neutral posture, thus possibly changing the nature of the spinal loads. However, the additional sagittal flexion and lateral velocities may increase the coactivity of the trunk muscles, ultimately increasing the spinal loads. The effect of these changes on spinal load is unknown.

Investigations of the interaction between asymmetry and number of hands has been limited to one-sided asymmetry (Allread *et al.* 1996). Work conditions sometimes require the worker to reach across the body to grab and lift an object. The present review has not identified any studies that have assessed spinal loading under these types of lifting situations.

Thus, the objective of this study was to investigate how spinal loading develops during asymmetric lifting when the lift origin was positioned to either the left or the right of the sagittal plane and while using either one or two hands to perform the lift. These findings are expected to have significant implications for workplace design.

2. Methods

2.1. *Approach*

This study explored spinal loading as subjects lifted from a sagittally symmetric lift origin and two asymmetric origins (on each side of the body) to a sagittally symmetric lifting destination. Subjects were asked to perform all lifts using both a one-handed as well as a two-handed lifting technique while standing upon a force plate. Trunk muscle electromyographic (EMG) activity was recorded while the subjects performed the lifts. This information was used as input to an EMG-assisted model that predicted spinal loading in three dimensions.

2.2. *Subjects*

Ten males volunteered to participate in this study. None of the subjects had any significant history of low-back pain. The mean (SD) age, height, and weight of the subjects were 26.8 (4.6) years, 168.3 (21.0) cm, and 80.9 (3.6) kg, respectively.

2.3. *Experimental design*

The experimental design consisted of a two-way, within-subject design. The independent variables were lift origin asymmetric position (asymmetry) and the number of hands used to perform the lift. Subjects served as a random effect.

Asymmetric origin was operationally defined according to the Revised NIOSH Lifting Equation (Waters *et al.* 1994). The asymmetry conditions consisted of lift origins located in a sagittally symmetric position (0°), 30 and 60° to the right of the mid-sagittal plane, and 30 and 60° to the left of the mid-sagittal plane. These lift origins are shown graphically in figure 1. The lift origins were positioned at a vertical height of 50.8 cm off the ground and at a horizontal distance of 53.3 cm from the centre of the box to the spine. Thus, the handles of the box were approximately aligned with knee height. The lifting techniques consisted of using one hand or two hands when lifting a standard box. The standard box weighed 13.6 kg. The box was constructed of wood with two outside handles used during two-hand lifts and one inside handle used during one-hand lifts. All handles were located at the same vertical height position (22.9 cm from the bottom of the box) and were 2.9 cm in diameter.

The dependent variables consisted of the spinal loads predicted from the EMG-assisted biomechanical model that has been developed over the last decade in the Biodynamics Laboratory (Marras and Reilly 1988, Reilly and Marras 1989, Marras and Sommerich 1991a,b, Granata and Marras 1993, Mirka and Marras 1993, Granata and Marras 1995a,b, Marras and Granata 1995, 1997, Davis *et al.* 1997). The model has been validated under forward trunk bending (Marras and Sommerich 1991a,b, Granata and Marras 1993, 1995a), trunk twisting (Marras and Granata 1995), and lateral bending (Marras and Granata 1997) motions. Recent studies (Marras 1997) have used MRI scans of subject trunk cross-sections to adjust the EMG-assisted model for differences in the cross-sectional area of the trunk muscles on the right and left sides of the body. The spinal loads estimated in this study were the maximum values of compression, anterior-posterior (A-P) shear, and lateral shear forces on the lower back at the lumbosacral joint (L5/S1).

2.4. *Apparatus*

Trunk motion data were recorded from a back electrogoniometer designed to measure lumbar sagittal flexion and lateral angles relative to the pelvis, thoracic sagittal and lateral angles relative to the lumbar region, and twist angle of the thorax relative to the pelvis. The output from this system coincides with motions from the lumbar spine, thoracic spine, and the sum of these two representing overall trunk

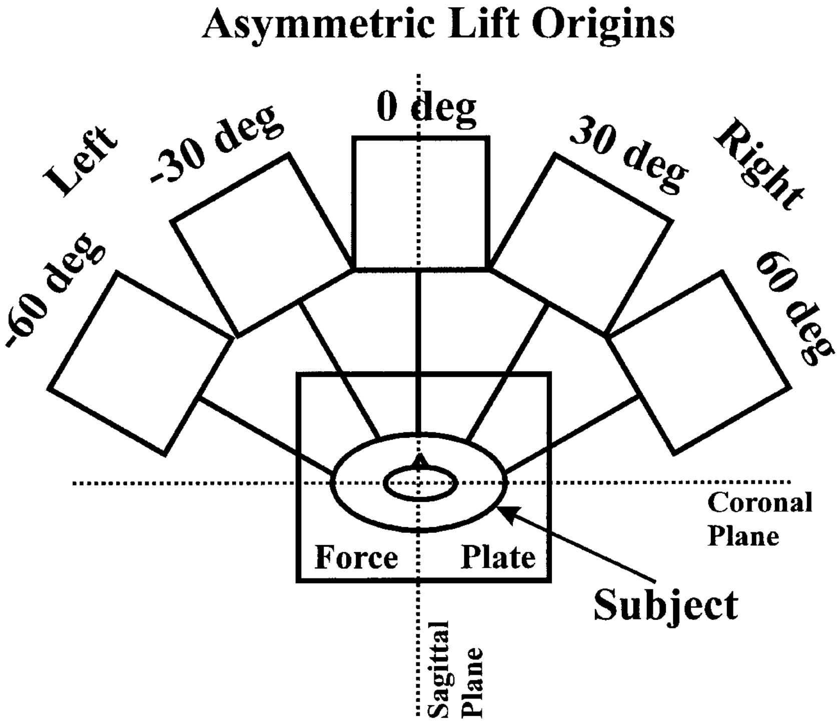

Figure 1. Asymmetric lifting origins.

motions in three dimensions. The sum of the trunk motion measured from this back goniometric system have been found to be identical to the 3-dimensional measurements from the Lumbar Motion Monitor (LMM).

Electromyographic (EMG) activity was collected through the use of bi-polar surface electrodes spaced approximately 3 cm apart and located at the ten major trunk muscle sites. These ten trunk muscles consisted of the right and left erector spinae (RES, LES), right and left latissimus dorsi (RLAT, LLAT), right and left internal obliques (RIO, LIO), right and left external obliques (REO, LEO), and right and left rectus abdominis (RRA, LRA). Standard electrode locations have been described by Mirka and Marras (1993). The raw EMG signals were pre-amplified, high-pass filtered at 30 Hz, low-pass filtered at 1000 Hz, rectified, and 'processed' via a 20 ms sliding window hardware filter.

A force plate (Bertec 4060A) along with a pelvic elctrogoniometer system were used to monitor moments imposed about the L5/S1 joint during the lifts. The electrogoniometer system measured the relative position of L5/S1 with respect to the centre of the force plate, along with the subject's pelvic angle (Fathallah *et al.* 1997). A picture of the subject instrumented under these experimental conditions is shown in figure 2.

All signals were collected simultaneously using customized Windows^{TM}-based data acquisition software developed in the Biodynamics Laboratory. The signals were digitized at 100 Hz using an analogue-to-digital (A/D) board in conjunction with a 486 portable computer.

2.5. *Procedure*

After a brief subject orientation, the EMG electrodes were affixed to the subject's trunk using standard placement procedures and skin resistances were assessed

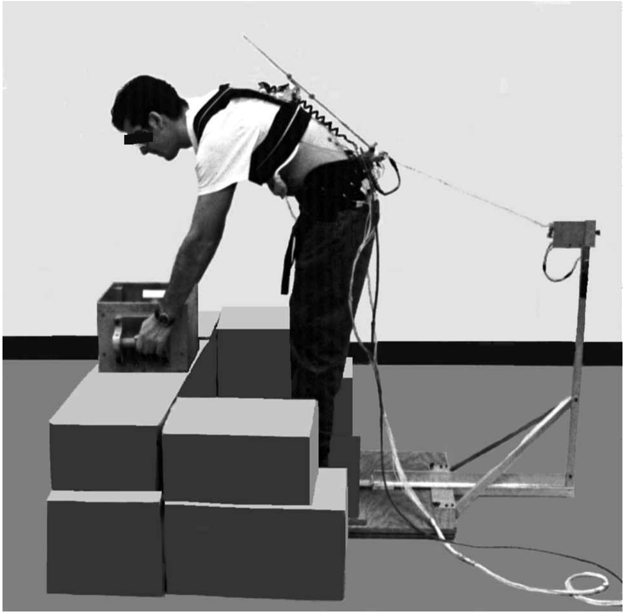

Figure 2. Subject performing two-handed symmetric lift.

(Marras 1990). The subjects were then positioned in a structure where they performed six standard maximum (calibration) exertions used to normalize the EMG activities. The six exertions consisted of sagittal extension with the trunk at a 20° forward flexion angle, sagittal flexion at 0° flexion, right lateral bending at 0° flexion, left lateral bending at 0° flexion, right twist at 0° flexion, and left twist at 0° flexion. After each maximum exertion, 2 min of rest were permitted to minimize the effects of fatigue (Caldwell *et al.* 1974).

Next, subjects were positioned on the force plate and the pelvic electrogoniometer system was affixed to the subject. Subjects were then given lifting instructions. The standard box was lifted from a randomly determined asymmetric origin to a sagittally symmetric destination. All conditions were repeated twice. Rest periods were provided between lifts and the subjects were encouraged to alert the researchers when more rest time was needed.

2.6. *Data analyses*

The voltages collected from the electrogoniometer systems were converted into angles, velocities, and accelerations through a customized conversion software. The EMG data were normalized with respect to the maximum output of the muscles (obtained during the calibration exertions). The EMG and kinematic data were used by the EMG-assisted model to calculate spinal forces and moments imposed on the lumbosacral joint (L5/S1). The model predicted trunk moments were compared with those measured by the force plate and goniometric system and used as a model performance measure.

Univariate descriptive statistics were reviewed for all dependent measures and used to ensure data quality. Analysis of variance (ANOVA) procedures were used to evaluate the statistical significance of all the dependent variables. *Post-hoc* follow-up procedures (Tukey multiple pairwise comparisons) were used to identify the source of significant effect(s).

3. Results

3.1. *Model performance*

Mean (SD) R^2 values between model predicted and force plate measured trunk moments were 0.89 (0.15), with an average absolute error (AAE) value of 10.88 (6.38) Nm. The mean gain predicted for subjects was 39.6 (17.7) N/cm^2. These measures indicated that the model performed extremely well under the experimental conditions.

3.2. *Spinal loading*

A summary of the statistically significant differences observed in this study are shown in table 1. The results of the analyses indicated that changes in asymmetry signficantly influenced the spinal loads in all three dimensions. The number of hands used in the lift significantly affected spinal compression but not lateral shear or A-P shear at the $p < 0.01$ level. However, a statistically significant interaction between the asymmetry conditions and the number of hands employed during the lift was observed for compression, lateral shear, and A-P shear.

The magnitude of the compressive loads imposed upon the spine is described as a function of both lifting asymmetry and the number of hands used to perform the lift in figure 3. Under all asymmetries, two-handed lifting resulted in the highest compressive loads on the spine compared to one-handed lifting. However, the

Table 1. Summary of statistical significance for the three-dimensional spinal loading measures.

	Lateral shear force	Anterior-posterior shear force	Compression force
Lift origin asymmetry (A)	0.0001*	0.0001*	0.0001*
Hands (H)	0.61	0.03	0.0001*
A × H	0.0006*	0.0001*	0.0001*

*Indicates significance at $p < 0.01$.

magnitude of difference in compressive loading using one or two-hands changed dramatically at the various asymmetries. The figure indicates that under sagittally symmetric lifting conditions (0°), the use of one-hand to perform the lift decreases compression on the spine by about 5% compared to two-handed lifting. At both 30° asymmetry conditions, the differences between lifting with two hands and lifting with the (one) hand opposite the direction of the asymmetric lift (using left hand for right asymmetric lifts and right hand for left asymmetric lifts) was insignificant. However, when the hand on the same side as the asymmetric origin was used for the one-handed lifts (right hand for right asymmetry and left hand for left asymmetry), the reduction in compression compared to the two-handed lifts was about 13%. A similar trend was observed for the 60° asymmetric lifting origin conditions. Under these conditions, no statistically significant differences were observed between two-handed lifting and one-handed lifting when the hand opposite the asymmetric origin was involved in the lift. However, when the hand on the same side as the asymmetric origin was employed during the lift, a 17% drop in mean peak compression was observed when the lift origin was located to the left and a 21% decrease in mean peak compression was observed when the lift origin was located to the right.

When the effect of asymmetry alone was considered, significant changes were present when lifting from the left compared to the right. Relative to the 0° asymmetry condition, the mean peak compressive load on the spine increased by 3% and 5% when lifting from lift origins positioned at 30° and 60° to the right of the sagittal plane. Mean peak compressive load increased by 6% and 9% when lifting from the 30° and 60° left origins, respectively. When the effect of the number of hands used in the lift was considered, a difference was noted in the hand used. Relative to the two-hand lift, mean peak compression decreased by 8% when the right hand was used, whereas mean peak compression was decreased by 3% when the left hand was used.

An interesting difference between the asymmetries and the number of hands involved in the lift was observed when spinal lateral shear forces were considered. These differences are shown in figure 4. Under sagittally symmetric conditions, lateral shear was greatest when both hands were involved in the lift as was the case for spinal compression. When lifting with the right hand only at the 0° asymmetry lateral shear was reduced by 24%. Lifting with the left hand under the 0° condition resulted in a lateral shear reduction of 15%. Relative to the 0° lifting origin, lifting from an origin located 30° to the right of the sagittal plane increased lateral shear by a mean of 35%. Lifting with the left hand alone in this position decreased lateral shear by 20% compared to lifting with two hands or the right hand alone. When the lift origin was located 60° to the right of the sagittal plane, the mean increase in

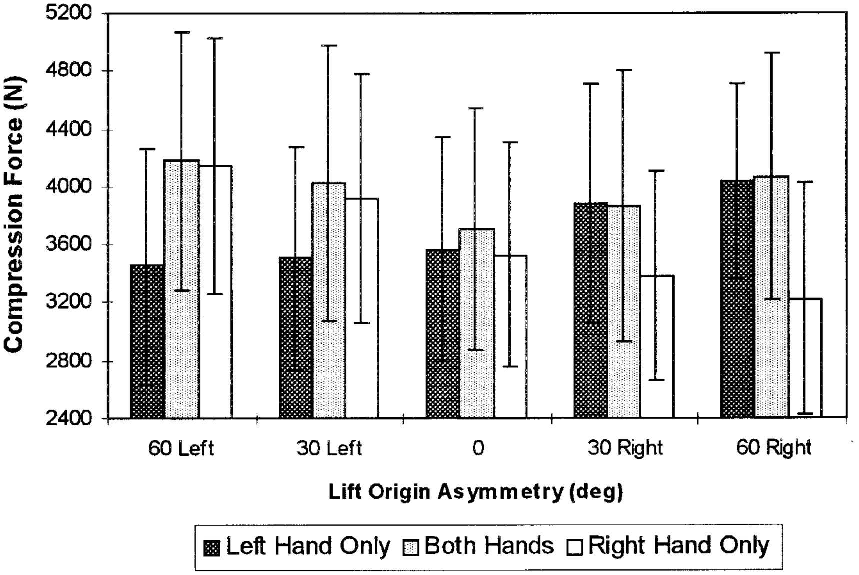

Figure 3. Mean peak compression force and standard deviations as a function of lift origin asymmetry and the number of hands used to lift the box.

lateral shear increased by 58% relative to the 0° asymmetry origin. As with the 30° right asymmetric origin, when the left hand was used to lift at the 60° right lift origin, the lateral shear decreased by 16% compared to the two-hand or right-hand lift. Lifting from origins located to the left of the sagittal plane resulted in even greater lateral shear loading. Increases of 62 and 76% in mean lateral shear were observed when lift origins were located at 30° and 60° to the left of the sagittal plane, respectively. When lifting from lift origins located to the left of the sagittal plane, the hand involved in the lift had an even greater influence on lateral shear. Lifts from the 30° left asymmetry yielded greatest lateral shear forces when lifting with the left hand. These mean peak shear forces were 16% greater than lifting with two hands. Whereas, lifting with the right hand resulted in lateral shear forces that were 23% less than lifting with both hands. Lifting from origins located at a point 60° left of the sagittal plane resulted in similar trend but of slightly greater magnitude. Lifting with the left hand in this position resulted in mean lateral shear forces that were 19% greater than lifting with both hands. Using the right hand to lift decreased lateral shear by 27% .

The impact of lift origin asymmetry and number of hands used in the lift upon A-P shear forces is shown in figure 5. Asymmetric origin location had more of an impact of A-P shear than did the interaction with hands involved in the lift. Compared to the sagittally symmetric lift origin, lifting from an origin located 30° to the right of the sagittal plane decreased the A-P shear by 4.5% . If the lift origin was located 60° to the right of the sagittal plane, the average peak A-P shear force was reduced by nearly 8% relative to the 0° origin. Asymmetric origin and hand use interactions were not statistically different for lift origins located at 0°, 30° right, or 60° right of the sagittal plane. Asymmetric origins to the left were only different between the 0° condition and the 60° left asymmetric origin. Lifts from this position

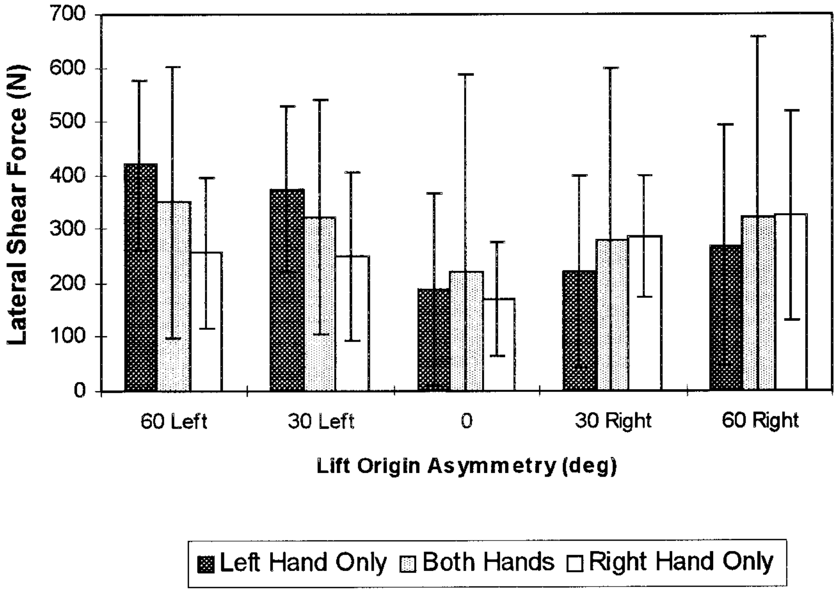

Figure 4. Mean peak lateral shear force and standard deviations as a function of lift origin asymmetry and the number of hands used to lift the box.

decreased A-P shear by a mean of 5% . At this lift origin, lifting with the left hand or both hands decreased A-P shear by 3 to 5% compared with lifting with the right hand alone. A similar difference was noted at lift origins located at 30° to the left.

4. Discussion

Previous studies that have investigated the influence of asymmetric lifting have approached the issue in one of two ways. They have either defined asymmetry relative to the workplace and not evaluated muscle activities and spinal loading or have defined asymmetry relative to the frame of reference of the spine and evaluated muscle activities or spinal loading but have not related the issue to the workplace. This study has been able to incorporate both approaches by relating relative spinal loading, trunk kinematics, and muscle activities to the layout of the workplace.

These results have shown that the issue is complex. By evaluating combinations of asymmetric lift origin and the number of hands involved in the lift, significant trade-offs have been identified between these two workplace variables. These findings have indicated that compression and lateral shear increase with increases in lift origin asymmetry, whereas A-P shear decreases in lift origin asymmetry. In order to consider these findings in perspective one must view the results relative to the spine's tolerance limits. This study employed one weight for all conditions (13.7 kg). However, as the external load changes in magnitude, the relative relationship between the tolerances in the various planes would be expected to remain relatively constant. A range of spine compression tolerance limits have been reported by Jager (1987). One of the commonly cited limits is that from the NIOSH (1981). According to NIOSH, the tolerance level for compression loading of the spine is expected to be around 3400 N. At this level of compression, microfractures of the vertebral

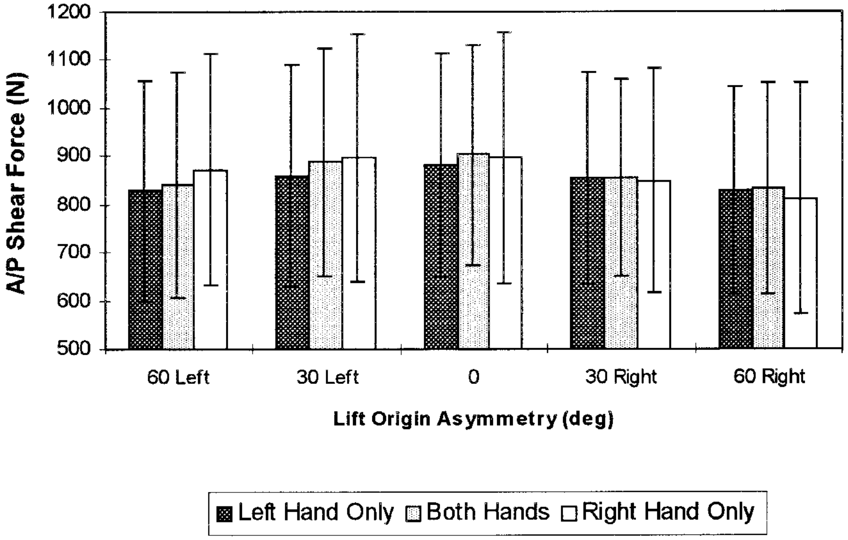

Figure 5. Mean peak anterior-posterior shear force and standard deviations as a function of lift origin asymmetry and the number of hands used to lift the box.

endplate are believed to begin to occur. Once the compression load reaches 6400 N about 50% of workers would be expected to develop vertebral endplate microfractures. The results of this study indicate that the mean peak compressive load for most conditions exceeded this 3400 N limit. If one considers the range of values observed via the standard deviation of compression, it is obvious that a large percentage of the loadings would be expected to exceed the 2400 N limit. Thus, compressive load should be a measure that is weighted heavily when interpreting these results.

The threshold limits for spine lateral and A-P shear are not as well documented as those for compression. McGill (1996) reported that the spine (disc) tolerance to shear loading would be expected to be approximately 1000 N. There may also be reasons to suspect that different tolerance limits may exist for lateral shear compared to A-P shear. The construction of the vertebrae with its neural arch adds considerable resistance to forward shear; however, lateral shear strength, which relies more on disc strength, is probably less than 900 N (Farfan 1988). Furthermore, conventional wisdom indicates that combined loadings should be considered when evaluating spinal loading. The literature is rich with studies indicating that disc strain increases greatly with lateral loading and with increases in combined plane loading (Broberg 1983, Lin *et al.* 1978, Schultz *et al.* 1979, Shirazi-Adl 1989, 1991, Shirazi-Adl and Drouin 1987, Shirazi-Adl *et al.* 1986).

In this study, the mean peak lateral shear forces were well below this tolerance range. However, the mean peak A-P shear forces approached the 900 N limit. Thus, factors that reduce A-P shear forces and compressive loading, individually as well as collectively, should be considered a priority when interpreting the results of this study. This study has demonstrated the importance of designing lifting tasks that require minimal amounts of task asymmetry. Spinal compression increased between

3 and 9% compared to sagitally symmetric lifting and A-P shear decreased by about the same amount for a given asymmetry. Thus, a significant trade-off must be considered.

However, these results were greatly affected by the hand used to perform the lift. Here, we see that lifting using the hand on the same side of the body as the symmetric lift origin decreases both compression and A-P shear compared to lifting with two hands or lifting across the body with the opposite hand. These results indicate that compression is reduced by 5% when lifting with one-hand in the sagitally symmetric position to as much as 21% when lifting with the right hand from an asymmetric origin located at 60° to the right of the sagittal plane. Reductions in A-P shear were also noted when using one hand but the magnitude of these differences were smaller. Lateral shear increased under these conditions but the magnitude of these mean peak lateral shears were well within the tolerance limits. Thus, these results indicate that there is a benefit to one-handed lifting. Even though compression increases with increases in the asymmetric origin of the lift, the compressive load can be mediated by simply lifting with the hand on the same side as the asymmetric origin. In fact, these values were comparable to those observed during sagitally symmetric lifting.

Significant differences in spinal loading were also noted when comparing lift origins located to the right versus the left of the sagittal plane. Increases in peak compression values were about twice as great when lifting from origins located to the left of the sagittal plane compared to lifting from origins to the right of the sagittal plane.

In-depth analyses revealed that the differences in spinal loads observed among the various asymmetric origin and hand conditions can be explained by several factors. First, the external trunk moment increased as the task asymmetry increased. The trunk moment was found to change significantly as a function of the kinematics of the lift. The maximum lateral and twisting positions, velocities, and accelerations were found to increase significantly with increases in asymmetry, which would all increase the resultant trunk moments. In general, the kinematic variables were similar for lift origins located to the right and the left of the sagittal plane (table 2). However, hip motion altered the resultant moment and was influenced by asymmetry. The hips were more rotated and flexed forward when lifting from greater asymmetric origins, especially when the lift origin was 60° to the left of the sagittal plane.

Second, the activity of the ten trunk muscles were significantly affected by the location of the asymmetric origin. More asymmetric lifting origins resulted in increased levels of coactivity. The right latissimus dorsi, right erector spinae, right internal oblique, and right external oblique muscles all exhibited increased activity when lifting from origins located to the left of the sagittal plane (figure 6). When differences in external moments associated with the right and left lifting origins were accounted for, the EMG activity levels between the two sides of the body were still found to be different. More coactivity occurred when lifting from origins to the left compared to lift origins located to the right of the sagittal plane. These muscle activity patterns were similar to those found by Marras and Mirka (1992) for asymmetric lifting.

Third, further evaluation of the data revealed that the trunk moments and muscle activities were significantly altered by the number of hands used in the lifts. The resultant trunk moment was lowest for the right-hand exertions and greatest for the two-hand conditions. Both maximum sagittal trunk position and hip flexion were

Table 2. Means (standard deviations) of the maximum trunk and hip kinematics as a function of lift origin asymmetry.

	Lift Origin Asymmetry				
	Left		Symmetrical	Right	
	60°	30°	0°	30°	60°
Trunk sagittal plane					
Position	40.6 (19.5)	41.0 (17.8)	42.7 (18.1)	42.4 (17.4)	41.5 (18.5)
Velocity*	49.1 (16.8)	49.7 (16.5)	57.0 (18.7)	51.5 (17.0)	48.0 (16.2)
Acceleration*	105.9 (32.7)	105.6 (36.4)	118.2 (35.2)	106.4 (36.2)	105.4 (35.1)
Trunk lateral plane					
Position*	– 15.3 (10.6)	– 10.35 (11.1)	0.2 (15.6)	10.5 (13.6)	14.7 (16.0)
Velocity*	15.5 (25.0)	12.9 (22.0)	2.9 (25.2)	– 11.0 (20.4)	– 18.0 (18.3)
Acceleration*	5.4 (112.3)	25.1 (88.9)	4.3 (121.0)	– 16.3 (67.9)	– 17.5 (84.0)
Trunk twisting plane					
Position*	7.9 (12.9)	5.8 (11.3)	0.2 (9.3)	– 5.9 (11.0)	– 8.8 (12.1)
Velocity*	– 14.9 (9.8)	– 10.1 (10.3)	– 1.3 (10.0)	7.7 (11.6)	12.3 (11.1)
Acceleration*	– 17.7 (54.8)	– 21.2 (50.6)	– 3.1 (46.6)	18.8 (50.8)	13.9 (52.2)
Hip flexion					
Position*	25.7 (11.7)	21.3 (10.3)	16.8 (9.4)	16.7 (9.4)	19.8 (10.5)
Velocity*	40.5 (18.0)	31.0 (13.2)	29.8 (12.8)	26.6 (11.9)	31.7 (14.3)
Acceleration*	91.0 (49.0)	63.8 (38.6)	74.0 (32.3)	60.1 (33.8)	69.4 (41.7)
Hip rotation					
Position*	29.3 (10.0)	19.2 (12.5)	1.0 (11.9)	– 20.6 (15.2)	– 32.6 (12.9)
Velocity*	– 51.8 (23.1)	– 35.7 (23.9)	– 0.6 (25.6)	30.9 (22.5)	44.6 (28.4)
Acceleration	– 54.5 (194.9)	– 69.5 (154.3)	– 28.5 (111.2)	– 34.0 (109.0)	– 47.6 (156.9)

*Indicates a significant difference between asymmetric conditions was present ($p < 0.05$).

greater for the two-hand conditions than the one-hand exertions. Conversely, the one-hand exertions produced greater twisting and hip rotation as compared to two-hand lifting. Descriptive statistics of trunk and hip motions as a function of the number of hands used during the lifts are presented in table 3. Almost all of the trunk muscle activities were affected by the number of hands used in the lift (table 4). Left-hand lifts were observed to increase muscle activities in the right latissimus dorsi, the right erector spinae, and the right internal oblique, and decrease activities in the left erector spinae and the left internal oblique as compared to either right-hand or two-hand exertions. The opposite pattern was observed for right-hand lifts. Thus, as compared to two-hand lifting, the one-hand conditions produced a different loading pattern that resulted from a combination of increased trunk moments and different muscle coactivity.

The increased coactivity observed for the muscles located on the right side of the body in conjunction with the differences in the cross-sectional areas of these muscles (on opposite sides of the body) and the differences in imposed moment help to explain the increased compressive load experienced by the spine when lifting from origins located to the left of the sagittal plane.

These results suggest that more realistic modifiers might be developed for use in lifting guides. For example, the Revised NIOSH Lifting Equation (Waters *et al.* 1994) mediates lifting limits by about 10% for every 30° of asymmetry involved in the lift regardless of whether lift origin occurs on the left or right of the sagittal plane. This study indicates that an adjustment factor is unncessary if the lift is

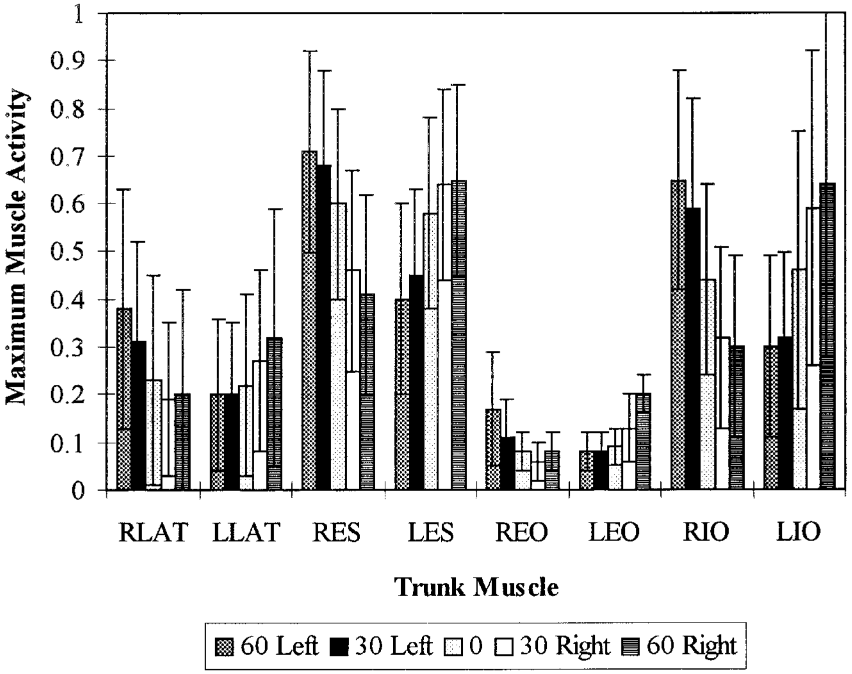

Figure 6. Mean muscle activities and standard deviations for the eight major trunk muscles as a function of lift origin asymmetry. (RLAT: Right Latissimus Dorsi; LLAT: Left Latissimus Dorsi; RES: Right Erector Spinae; LES: Left Erector Spinae; REO: Right External Oblique; LEO: Left External Oblique; RIO: Right Internal Oblique; LIO: Left Internal Oblique).

performed with the hand that is on the same side as the asymmetric origin. The results also show that lifts to the left of the sagittal plane are not just a mirror image of those to the right of the sagittal plane. If two hands are used, this study suggests that the discounting factor might be different for lift origins occurring to the right compared to the left of the sagittal plane. If lift origins occur to the right of the sagittal plane, a more appropriate discounting factor, based upon compression, might be 5% per 30° of asymmetry (up to 60° of asymmetry). Lift origins to the left of the sagittal plane require larger discounting factors that are not necessarily linearly related to the degree of asymmetry. Based upon the compression loading observed in this study, a lift origin located 30° to the left should discount the load by as much as 9%, whereas, an origin located 60° to the left would discount the load by up to 13%.

In order to extend the results of this study to a broader range of asymmetries, the subjects in this study were asked to perform additional lifts. These involved lifts from two asymmetric lift origins located to the right of the sagittal plane at 90° and 135°. When subjects lifted with their right hand only, no statistically significant differences in spine compression were noted. When the subjects lifted with both hands from a lift origin located at 90° to the right of the sagittal plane mean compression increased by 24% compared to lifting with two hands in a sagittally symmetric position. When lifting with two hands from a position located 135° to the right of the sagittal plane,

Table 3. Means (standard deviations) of the maximum trunk and hip kinematics as a function of number of hands used in lifts.

	Lifting technique Left hand	 Both hands	 Right hand
Sagittal plane			
Position (°)*	39.4 (17.4)	46.3 (19.5)	39.2 (16.8)
Velocity (°/s)*	50.2 (17.5)	55.1 (17.0)	47.9 (16.7)
Acceleration (°/s^2)	110.9 (36.3)	110.3 (33.7)	103.7 (36.0)
Lateral plane			
Position (°)*	– 4.7 (16.7)	– 2.7 (19.3)	7.2 (14.7)
Velocity (°/s)*	16.1 (26.4)	1.8 (20.2)	– 16.5 (19.28)
Acceleration (°/s^2)	7.1 (106.9)	8.2 (102.2)	– 14.7 (81.2)
Twisting plane			
Position (°)*	– 11.4 (8.8)	0.7 (10.4)	10.3 (9.5)
Velocity (°/s)	– 0.5 (15.5)	– 1.0 (14.0)	– 2.3 (14.5)
Acceleration (°/s^2)*	28.0 (52.4)	– 2.2 (43.8)	– 31.1 (46.6)
Hip flexion			
Position (°)*	17.5 (9.6)	22.3 (10.4)	20.3 (11.8)
Velocity (°/s)*	27.2 (13.8)	35.5 (11.4)	33.0 (17.7)
Acceleration (°/s^2)*	63.3 (38.2)	77.9 (28.4)	73.8 (51.5)
Hip rotation			
Position (°)*	– 12.9 (23.6)	– 1.2 (27.6)	11.9 (21.9)
Velocity (°/s)*	15.5 (42.3)	– 1.9 (44.5)	– 21.1 (39.1)
Acceleration (°/s^2)	– 50.3 (152.5)	– 51.8 (140.7)	– 38.3 (153.9)

*Indicates a significant difference between asymmetric conditions was present ($p < 0.05$).

mean compression increased by 30% compared to a sagitally symmetric lift. The trends observed in this study are contrasted to the modulation factors (multipliers) suggested in the Revised NIOSH Lifting Equation for the conditions explored in this study in figure 7. This evaluation indicates that any factor intended to mediate risk associated with asymmetric lifting should not only consider which hands are involved in the lift and the lift direction (asymmetry) but must also include a nonlinear modulation factor if two hands are used. The allowable load should be mediated by a much greater extent once the work asymmetry increases beyond 60° (from the right of the sagittal plane).

Several potential limitations of the study should also be addressed. First, subjects performed the tasks while their feet were stationary on a force plate. Thus, the results would be most applicable to lifting while the feet of the worker do not move at a workplace (i.e. lifting into a bin or working on an assembly line). If the feet were permitted to move, changes in lift kinematics and muscle recruitment would be expected to occur. Further studies should evaluate the effect of asymmetry and one versus two-hand lifting on spinal loading while the subjects are able to move their feet. It would be expected that the actual kinematic motions would be reduced, thus reducing the effects of asymmetry.

Second, the range of asymmetry was limited to 60° of asymmetric lift origin to the left of the sagittal plane and 135° of lift origin asymmetry to the right of the sagittal plane. The asymmetries within 60° of the sagittal plane reflect what has been commonly observed in industry (Marras *et al.* 1993). These findings should not be extrapolated beyond the asymmetric range observed in this study.

Third, the weight of the box was held constant at 13.6 kg. The current study estimated the loading on the spine. Although the results indicate that using the hand

Table 4. Means (standard deviations) of the maximum normalized muscle activities of the 10 major trunk muscles as a function of lift origin asymmetry and the number of hands used in the lift.

	Lift origin asymmetry				
	Left		Symmetrical	Right	
	60°	30°	0°	30°	60°
Left latissimus dorsi					
Left hand	0.13 (0.09)	0.15 (0.09)	0.19 (0.19)	0.19 (0.12)	0.23 (0.23)
Both hands	0.13 (0.08)	0.12 (0.05)	0.13 (0.08)	0.17 (0.10)	0.27 (0.21)
Right hand	0.35 (0.19)	0.32 (0.18)	0.36 (0.20)	0.45 (0.26)	0.47 (0.29)
Right latissimus dorsi					
Left hand	0.54 (0.24)	0.50 (0.22)	0.40 (0.30)	0.31 (0.18)	0.30 (0.15)
Both hands	0.29 (0.24)	0.19 (0.09)	0.13 (0.08)	0.12 (0.08)	0.14 (0.12)
Right hand	0.30 (0.20)	0.23 (0.14)	0.18 (0.11)	0.15 (0.11)	0.15 (0.30)
Left erector spinae					
Left hand	0.23 (0.13)	0.30 (0.13)	0.51 (0.18)	0.59 (0.20)	0.64 (0.20)
Both hands	0.43 (0.13)	0.47 (0.15)	0.59 (0.17)	0.66 (0.20)	0.66 (0.18)
Right hand	0.56 (0.17)	0.58 (0.15)	0.66 (0.16)	0.68 (0.18)	0.66 (0.20)
Right erector spinae					
Left hand	0.71 (0.21)	0.73 (0.20)	0.70 (0.21)	0.60 (0.21)	0.54 (0.19)
Both hands	0.72 (0.20)	0.69 (0.18)	0.62 (0.19)	0.49 (0.17)	0.44 (0.16)
Right hand	0.68 (0.21)	0.63 (0.20)	0.47 (0.12)	0.28 (0.11)	0.23 (0.15)
Left rectus abdominus					
Left hand	0.07 (0.06)	0.07 (0.06)	0.10 (0.18)	0.08 (0.05)	0.09 (0.06)
Both hands	0.06 (0.03)	0.06 (0.02)	0.06 (0.03)	0.06 (0.03)	0.07 (0.03)
Right hand	0.14 (0.20)	0.13 (0.26)	0.10 (0.14)	0.07 (0.05)	0.10 (0.18)
Right rectus abdominus					
Left hand	0.08 (0.06)	0.09 (0.08)	0.10 (0.10)	0.14 (0.15)	0.13 (0.15)
Both hands	0.08 (0.03)	0.07 (0.03)	0.07 (0.03)	0.07 (0.03)	0.07 (0.04)
Right hand	0.10 (0.06)	0.09 (0.05)	0.09 (0.06)	0.09 (0.08)	0.09 (0.09)
Left external oblique					
Left hand	0.07 (0.04)	0.07 (0.04)	0.11 (0.17)	0.15 (0.06)	0.20 (0.10)
Both hands	0.07 (0.04)	0.07 (0.04)	0.06 (0.03)	0.12 (0.08)	0.21 (0.12)
Right hand	0.11 (0.05)	0.09 (0.04)	0.09 (0.04)	0.13 (0.06)	0.19 (0.18)
Right external oblique					
Left hand	0.13 (0.08)	0.09 (0.05)	0.10 (0.31)	0.08 (0.04)	0.09 (0.06)
Both hands	0.18 (0.15)	0.09 (0.07)	0.05 (0.02)	0.05 (0.02)	0.06 (0.03)
Right hand	0.20 (0.12)	0.15 (0.09)	0.08 (0.05)	0.07 (0.08)	0.10 (0.31)
Left internal oblique					
Left hand	0.15 (0.10)	0.19 (0.12)	0.38 (0.34)	0.51 (0.32)	0.59 (0.37)
Both hands	0.29 (0.15)	0.32 (0.16)	0.44 (0.24)	0.58 (0.34)	0.63 (0.32)
Right hand	0.46 (0.17)	0.44 (0.16)	0.57 (0.24)	0.69 (0.32)	0.71 (0.40)
Right internal oblique					
Left hand	0.76 (0.21)	0.72 (0.18)	0.60 (0.21)	0.47 (0.17)	0.44 (0.18)
Both hands	0.63 (0.22)	0.58 (0.22)	0.43 (0.13)	0.31 (0.14)	0.28 (0.11)
Right hand	0.58 (0.22)	0.48 (0.22)	0.30 (0.11)	0.18 (0.13)	0.17 (0.18)

on the same side of the body as the load would be less stressful than two-handed lifting, shoulder strength for one-hand lifting might not be sufficient. This might result in increases in risk of shoulder injuries even though back injuries might be reduced. Additionally, greater or lesser weight would be expected to change the body dynamics. Allread *et al.* (1996) found that an increase of 6.8 kg corresponded to approximately 1° of sagittal flexion, 2° of sagittal velocity, 2° of lateral bending, and

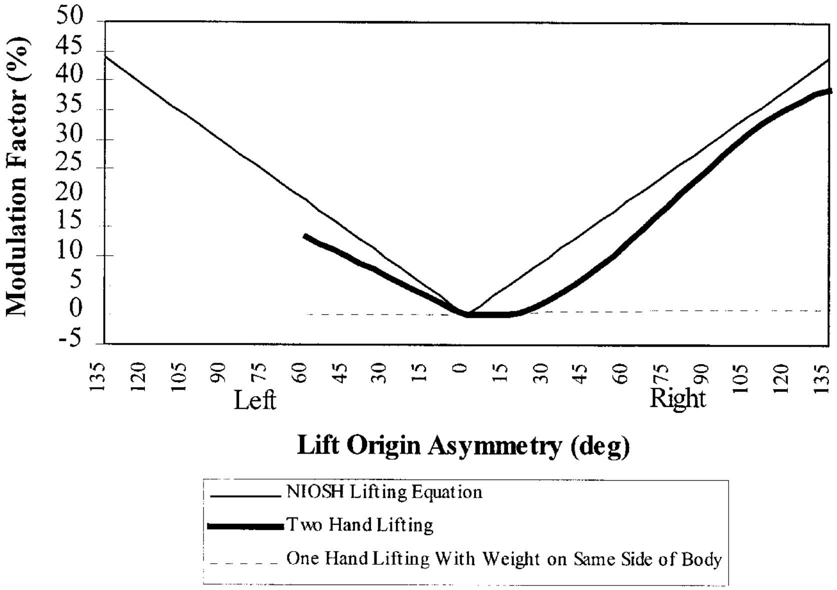

Figure 7. Asymmetric discounting factors for two-handed lifts and one-handed lifts as compared to the NIOSH (1991) factor.

2° of lateral velocity for asymmetric lifts. Thus, it would be expected that an increase in weight would only slightly effect the results of the current study.

5. Conclusions

In general, these results provided insight into the change of spinal loading as a function of lifting style and workplace parameters. More specifically, the following are the important findings of the study:

(1) Increased asymmetry corresponded to increased spinal loads. However, this was only true when both hands were involved in the lift or the lift was performed with the hand on the opposite side to the load reaching across the body. Lifting with the hand on the same side as the load did not increase loading significantly.
(2) Different loading patterns were observed when subjects lifted from locations to the right of the sagittal plane compared to lifting from locations to the left of the sagittal plane. For a given asymmetry, lifting from the left of the sagittal plane resulted in greater mean peak spine compression.
(3) When lifts were performed beyond 60° of asymmetric origin to the right of the sagittal plane, the relationship between spinal loading and asymmetric origin became nonlinear indicating much greater costs of lifting from origins beyond 60° off the sagittal plane.

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