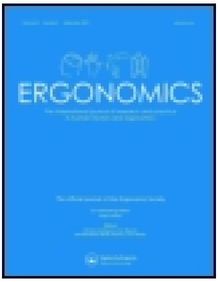

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Spine loading and trunk kinematics during team lifting

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Keywords: Team lifting; Spinal loading; EMG; Kinematics, Materials handling; Low back pain.

Two-person or team lifting is a popular method for handling materials under awkward or heavy lifting conditions. While many guidelines and standards address safe lifting limits for individual lifting, there are no such limits for team lifting, and these lifts are poorly understood. The literature associated with team lifting offers some interesting paradoxes. Many studies have indicated that people lift less per individual under team conditions compared with one-person lifting. Yet, at least one study has reported an increase in team-lifting capacity when subjects were height-matched. The current study explored the spine loading characteristics of one- and two-person lifting teams when subjects lifted under several sagittally symmetric and asymmetric conditions. Spine compression was lower for two person lifts for a given weight, while lifting in sagittally symmetric conditions whereas lateral shear became much greater for two-person lifts under asymmetric lifting conditions. This study has linked these changes to differences in trunk kinematic patterns adopted during one- versus two-person lifting.

1. Introduction

Two-person or team lifting is a popular method for handling materials when the capacity of an individual is expected to be exceeded by a lifting task. Many situations occur in the construction industry, the healthcare industry, the furniture handling industry and retail sales where it would be difficult to provide a mechanical lifting device due to the variety of lifting situations encountered. While numerous guidelines and standards address lifting limits for individual lifting situations, there are no such limits for team lifting. In addition, a review of the literature indicates that there is a poor biomechanical understanding of these lifts.

The literature associated with team lifting offers some interesting paradoxes. Karwowski and Mital (1986) and Karwowski and Pongpatanasuegsa (1986) reported that the sum of individual isometric and isokinetic lifting strengths was greater than the lifting capacity of the two-person team. Karwowski (1988) confirmed through psychophysical criteria that teams were willing to lift less than the sum of the individuals' maximum acceptable lifts. Sharp *et al.* (1995) extended this work by asking mixed gender and same gender teams to lift and carry a load. They found that mixed gender teams lifted 80% of the individual's lifting capacity sum, whereas same gender teams lifted $>90\%$ of this sum. Rice *et al.* (1995)

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developed regression equations that explained 90% of the variability. These equations indicated that the lifting capacity of the team is dictated by the weaker of the two team members. Johnson and Lewis (1989) have reported that during both team lifting and carrying, subjects were willing to lift weights that were greater than the sum of the individuals' acceptable weights. It is also interesting to note that Johnson and Lewis were the only ones that stated they matched subjects for height. They were also the only ones who found an increase in team-lifting capacity. Many of the previous studies intentionally mismatched subject anthropometry and found decreased team lifting capacity.

This review indicates some mixed results when considering team lifting from a strength and psychophysical perspective. However, none of the previous studies assessed how changes between one-person lifts and team lifts might affect the risk of low back disorder. It is likely that changes in lifting kinematics or lifting kinetics may be a result of changing from a one-person lift to a team lift. Lifting kinematics have been shown to be important indicators of work-related low back disorder risk (Marras *et al*. 1993, 1995). Kinetic evaluations of spine loading have also been widely accepted as a means to control low back disorders in the workplace (NIOSH 1981, 1991, Chaffin and Andersson 1991). We hypothesize that team lifting may alter trunk movements and the subsequent spinal loading that would presumably define risk of low back disorder. Therefore, the objective of this study was quantitatively to assess trunk kinematic changes and spine loading changes that might occur when lifting in teams compared with lifting individually.

2. Methods

2.1. *Subjects*

Ten male university students served as subjects for this study. Subject age ranged from 21 to 35 years of age. Average (SD) weight was 72.7 (±6.6) kg, whereas, average height was 176.7 (±4.2) cm. None of the subjects had a history of significant low back disorder. Note the small standard deviation associated with subject height in this study. Subjects' teams were matched for height as in the Johnson and Lewis (1989) study.

2.2. *Experimental design and task*

The experimental design consisted of a two-way, within-subject design. The independent variables were the number of team members involved in the lift and the degree of asymmetry involved in the lifting condition. The number of team members consisted of either a one- or two-person team lifting situations. The other independent variable consisted of the origin – destination configuration of the lift. Three lifting configurations involving different lifting asymmetries were specified and are described below. Subjects served as a random effect.

Subjects were asked to lift loads manually both individually and in two-person teams. The lifted load consisted of a 22.7 kg mass that was lifted by an individual and a 45.4 kg mass that was lifted by the two-person team. The weight for the one-person lift was placed in a box (30.5 × 28 × 23 cm) with handles positioned 45 cm apart. The weight for the two-person lift was placed in a 76 × 45 × 30.5 cm structure that permitted the handles to be positioned in the same location as in the one-person lift condition with two handles for each lifter. Three lifting tasks were specified for both the one-person and team lift conditions. These consisted of:

(1) A lift origin 52 cm off the floor positioned in the sagittal plane of the body a distance of 51 cm from the spine and lifted to a destination 107 cm off the floor and 25.4 cm in front of the spine but still in the sagittal plane of the body.
(2) A lift from the same origin as described in (1) but lifted to an asymmetric destination located at 36 cm lateral to each subject (in the coronal plane) and at a height of 135 cm off the floor.
(3) A lift from an asymmetric origin located 52 cm off the floor, 51 cm in front of the subject and 36 cm to the right of the subject then lifted to the asymmetric destination described in (2). Under each condition the subject was asked to place the load at a specified (fixed) destination. All subjects performed all lifting conditions while their feet remained stationary on the force plate. The subjects were only instructed about where to lift the box (from a given origin to a given destination) with no reference to lifting style.

As a follow-up to the team lift conditions, additional conditions were performed by all subjects. Under some of these conditions, team members attempted to synchronize their lifts. This was accomplished by allowing the team members to practice lifting together and also incorporating a 'count' into the lifting situation. Under another set of additional conditions the one-person lifts were performed while allowing the subject to place the lift in a position that they preferred instead of a specific fixed position at the destination. In still another set of additional conditions, subjects were asked to carry the load over 3.1 m. These additional lifting conditions were all performed after the original lifting conditions (non-synchronized lifts) were concluded.

2.3. *Apparatus*

Subject trunk motions were recorded with a lumbar motion monitor (LMM). This device documents three-dimensional torso motion on-line and has been previously described in the literature (Marras *et al.* 1992). A force plate (Bertec 4060A, Worthington, OH, USA) along with an electrogoniometer system attached to the pelvis were used to monitor the position of the L5/S1 joint relative to the force plate for some of the lifts. This information was used to monitor the moments imposed about the spine throughout the lift. However, this measurement was only feasible for the lifts that did not involve walking and carrying of the object. In addition, an electrogoniometer system documented the subject's pelvic angle during the lift. These systems were described by Fathallah *et al.* (1997).

Electromyographic (EMG) activity was collected through the use of bipolar surface electrodes spaced $\sim$3 cm apart and located at the 10 major trunk muscle sites. These trunk muscles consisted of the right and left erector spinae, right and left latissimus dorsi, right and left internal oblique, right and left external oblique, and right and left rectus abdominus. 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.

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

2.4. *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 (NIOSH 1991). 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 (where to lift the box). The appropriate box (for one- or two-person lifting) was presented to the subject(s) once the experimental condition was determined. All conditions were repeated twice. Rests were allowed between lifts and subjects were encouraged to alert the researchers when more rest was needed.

2.5. *Analyses*

During the two-person lifts, data were collected simultaneously for both individuals. The voltages collected from the electrogoniometer systems were converted into angles, velocities and accelerations through customized conversion software. The EMG data were normalized with respect to the maximum output of the muscles (obtained during the calibration exertions). These measures were used as input to an EMG-assisted model that has been under development in our laboratory over the past decade (Marras and Reilly 1988, Marras and Sommerich 1991a, b, Granata and Marras 1993, 1995, Marras and Granata 1995, 1997, Davis *et al*. 1997). Thus, the dependent measures in this study consisted of spine compression, A/P shear, and lateral shear about L_5/S_1 predicted by the model. In addition, the trunk and hip kinematics were used further to interpret model results. The model also predicted the moment imposed about the trunk. These moments were compared with those measured by the force plate and goniometric system and this information was used as a model performance measure.

All dependent variables were first summarized via descriptive statistics. These descriptive summaries included means ± SD of the maximum values observed. Analysis of variance (ANOVA) statistical analysis procedures were employed to identify significant differences among the dependent variables. When variables were identified as statistically significant post-hoc analyses (Tukey multiple pairwise comparisons) were employed to determine the source of the statistically significant effect.

3. Results

Statistically significant differences in spine loading were observed as a function of the experimental conditions. A summary of these differences is presented in table 1. Several components of spine loading about L_5/S_1 changed as a function of the experimental conditions. Table 1 indicates that spine compression varied as a function of the unique combination (interaction) of the number of team members and the degree of asymmetry involved in the lift. The nature of this relationship is shown in figure 1, which shows spine compression as a function of the task conditions and indicates that there are minimal differences in compression between one- and two-person lifts for the conditions involving an asymmetric component to the lift. However, the spine compression was significantly lower (~660 N lower) for two-person lifts when lifting under sagittally symmetric conditions. This compression trend is most likely related to the combination of the moments imposed about the sagittal plane (figure 2) and the lateral plane (figure 3). The sagittal plane moments (figure 2) were significantly lower during the two-person lifts under all lifting conditions. This trend was also apparent for the main effect of the number of team members. Conversely, the lateral plane moments were significantly greater during the two-person lifts (also the trend for the main effect) but only when the lifting condition involved an asymmetric destination. In addition, the lateral moments imposed about the spine were much smaller in magnitude under the symmetric lifting condition. This symmetric lifting condition also resulted in the lowest spinal compression. The mean maximum twisting moments were also observed to be lower for the two-person lifts (25 Nm) compared with the one-person lifts (32 Nm).

The difference between the one- and two-person moments imposed about the spine may be associated with several main effect differences noted among the kinematic variables (table 1). First, less hip flexion and hip flexion acceleration occurred with two-person lifting. Second, two-person lifts resulted in significantly less sagittal plane moment than did one-person lifts. Third, two-person lifts resulted in greater three-dimensional trunk velocity and acceleration. Thus, it appears that, in general, when two-person lifting occurred, the subjects would bend less from their hips and more from the back in the sagittal plane. This occurred by 'tucking in' their hips. The net result of this change in style would be to reduce the moment supported by the spine in the sagittal plane. This, in turn, would be expected to reduce the compressive load on the spine. In addition, when the remaining main effects of the number of lifting team members were examined it was particularly interesting to note that, besides the differences in sagittal plane kinematics, differences were associated with trunk twisting motions (position, velocity and acceleration). As was the case with the sagittal plane motions (noted above), these findings indicated that the amount of twisting motions increased when two-person lifting teams were employed.

Next, statistically significant differences occurred in spine compression, lateral shear and A-P shear as a function of the degree of asymmetry associated with a lifting condition regardless of whether one or two persons were performing the lift. The trend associated with this main effect was as expected with the sagittally symmetric lift producing the least amount of compression, lateral shear and A-P shear on the spine (figure 4). In general, all three components of spine loading were greatest when the lift involved an asymmetric origin and destination. Table 1 also indicated that the sagittal, lateral and twisting trunk moments all responded differently as a function of the asymmetry condition main effect. The trends associated with these variables were very similar to those associated with the spine loadings (figure 4). A similar trend also occurred with many of the kinematic variables found statistically significant in table 1. Sagittal position, lateral position, velocity and acceleration, twisting position and velocity, hip flexion velocity and hip rotation acceleration all exhibited a similar trend with respect to the asymmetry of the lift as shown in figure 4.

The major change in muscle recruitment patterns observed under these conditions involved an increase in the activity of the oblique muscles when asymmetric load destinations were included in a condition. The oblique muscle

Table 1. Statistical significance results from the analysis of variance (ANOVA) for the spine loading and trunk kinematic variables.

Effect	Maximum sagittal trunk moment (Nm)	Maximum lateral trunk moment (Nm)	Maximum twisting trunk moment (Nm)	Maximum resultant trunk moment (Nm)	Maximum lateral shear force (N)	Maximum A-P shear force (N)	Maximum compression force (N)
Number of lifters (LIFTER)	**0.0001**	**0.003**	**0.003**	**0.0001**	0.45	0.53	0.11
Asymetry (ASYM)	**0.005**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
LIFTER*ASYM	**0.02**	**0.0002**	0.33	**0.0001**	0.25	0.24	**0.01**

Effect	Maximum trunk sagittal position	Maximum trunk lateral position	Maximum trunk twisting position	Maximum trunk sagittal velocity	Maximum trunk lateral velocity	Maximum trunk twisting velocity	Maximum trunk sagittal acceleration	Maximum trunk lateral acceleration	Maximum trunk twisting acceleration
Number of lifters (LIFTER)	0.06	0.86	**0.0006**	**0.0001**	0.15	**0.02**	**0.01**	0.59	**0.04**
Asymmetry (ASYM)	**0.0002**	**0.0001**	**0.0001**	0.11	**0.0001**	**0.0001**	0.45	0.94	0.55
LIFTER*ASYM	0.45	0.88	**0.0002**	0.15	0.48	0.06	0.39	0.63	0.50

Effect	Maximum hip flexion position	Maximum hip rotation position	Maximum hip flexion velocity	Maximum hip rotation velocity	Maximum hip flexion acceleration	Maximum hip rotation acceleration
Number of lifters (LIFTER)	**0.01**	0.66	0.13	0.52	**0.04**	0.93
Asymmetry (ASYM)	0.72	**0.0001**	**0.0001**	**0.0001**	0.17	**0.0001**
LIFTER*ASYM	0.18	0.68	0.64	0.56	0.63	0.20

*Bold type indicates significant effect at $p < 0.05$.

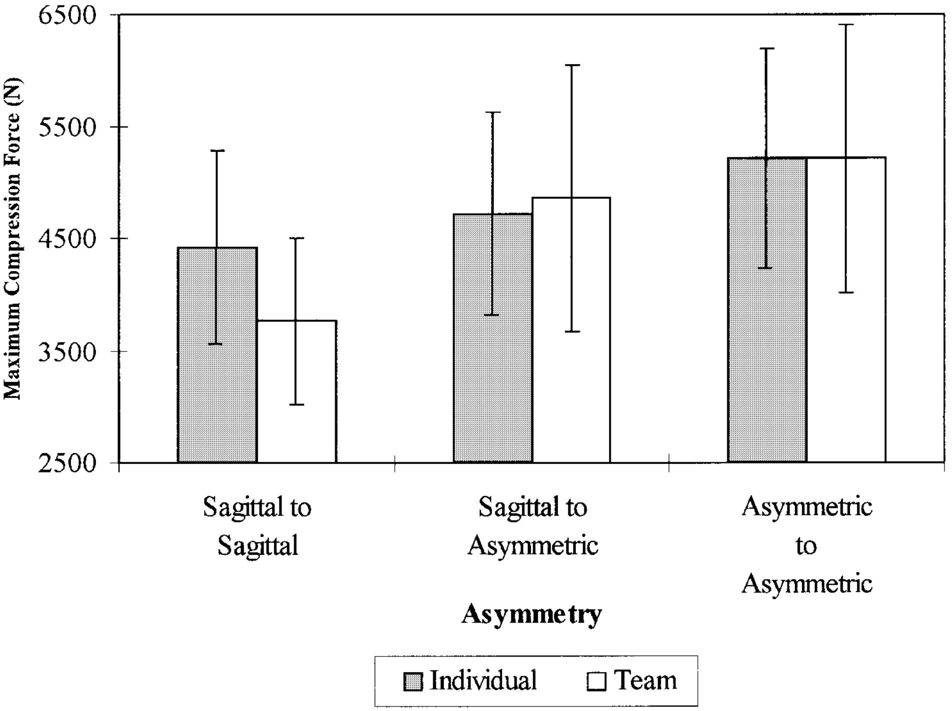

Figure 1. Maximum compression force as a function of the number of lifters and asymmetry (fixed destination for individual).

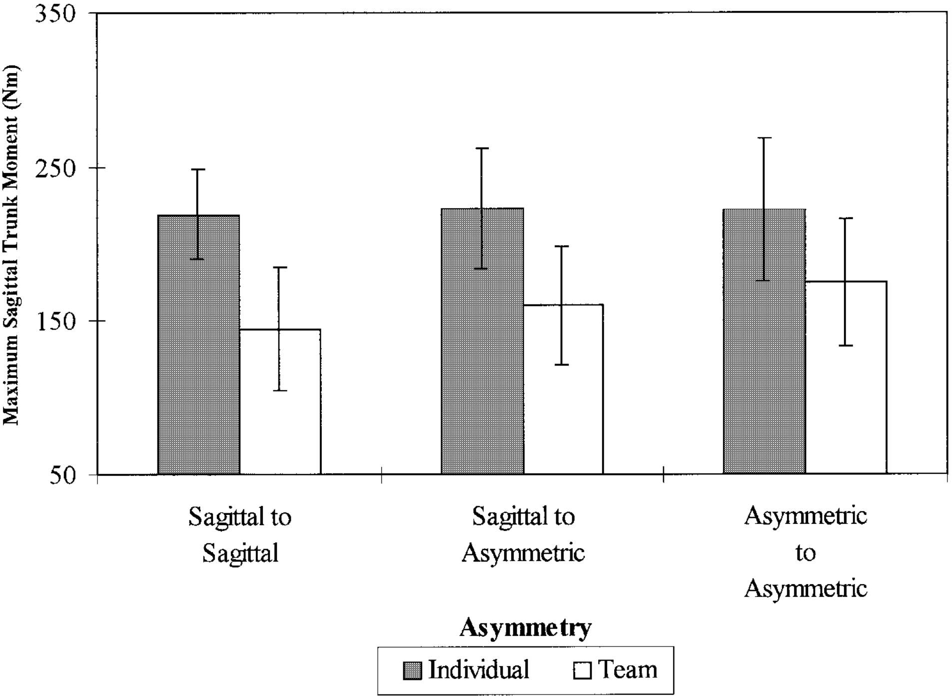

Figure 2. Maximum sagittal trunk moment as a function of the number of lifters and asymmetry (fixed destination for individual).

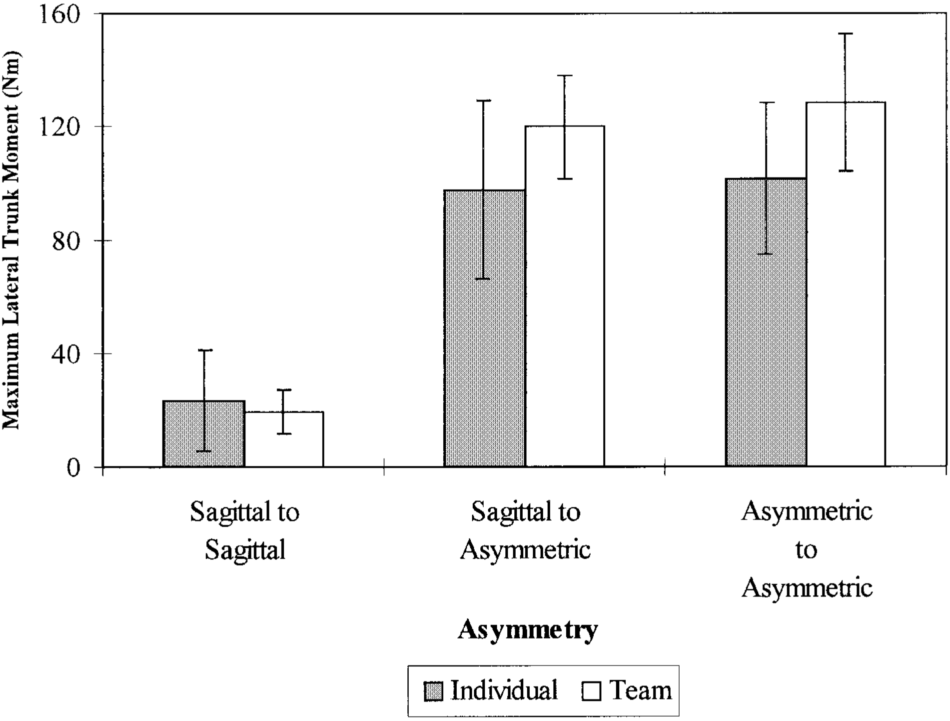

Figure 3. Maximum lateral trunk moment as a function of the number of lifters and asymmetry (fixed destination for individual).

activity increased by an average of 25% under these conditions. It is also significant to note that lateral spinal shear force increased to a level near the disc tolerance limit (McGill 1996) under asymmetric lifting conditions (figure 4).

4. Discussion

4.1. *General implications*

These findings have helped distinguish between the biomechanical consequences associated with one-person lifting compared with team lifting. These investigations have indicated that spine loading varies greatly for one- and two-person lifts as a function of the lifting conditions defined by the symmetric or asymmetric origin and destination of the load lifted. In general, only compression varied as a function of this interaction. For a given load lifted by an individual, two-person lifting only reduces compression when the lift is performed under sagittally symmetric conditions. It is also interesting that the magnitude of this decrease in compression was similar to the difference in lifting capacity observed by Johnson and Lewis (1989). As mentioned above, our subject teams were of similar stature as were those of Johnson and Lewis.

This study has shown that significantly different body kinematics are involved with a one- compared with a two-person lift. For two-person lifts, the individuals tended to 'tuck in' the pelvis and to move the trunk more rapidly resulting generally in a more vertical lift. This vertical trunk position along with greater trunk momentum (directed rearward) tends to minimize the sagittal moment imposed

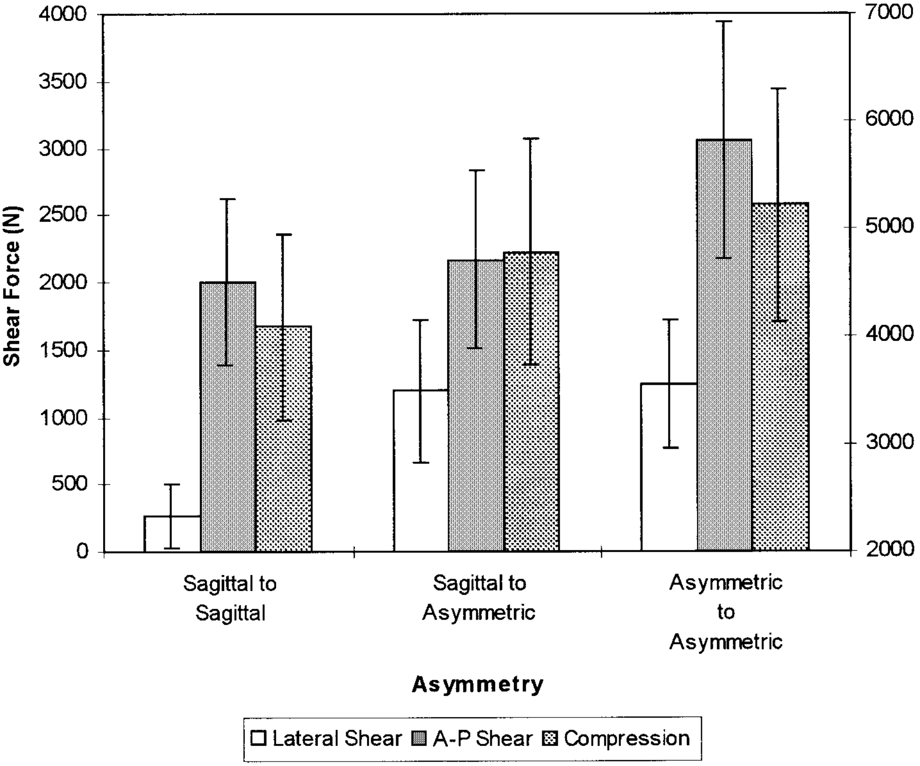

Figure 4. Maximum three-dimensional spinal loads as a function of asymmetry.

about the spine. In addition, the trunk musculature is at a more desirable length when the trunk is bent as opposed to the hips, as is the case in this situation. Thus, it appears that when lifting in a sagittally symmetric position, two-person teams coordinate their body kinematics differently. Two-person teams use less hip tilt and more trunk momentum to counterbalance the load. This difference in the 'kinetic chain of events' in turn minimizes the trunk moment and the subsequent trunk loading.

Thus, this investigation showed that the conditions of the lift dictate whether two-person lifts are beneficial or detrimental to spine loading. One could hypothesize that that there may be other components of the one- versus two-person lifting condition that may influence spinal loading. To investigate further the impact of these potentially significant components, several additional testing conditions were performed using the same subject pool.

4.2. *Precision of load placement*

One could speculate that the two-person lift requires much greater coordination, precision and control between lifters than would a one-person lift. It would be possible for a one-person lift to place, simply and smoothly (somewhat ballistically), the load at the destination point, whereas a two-person team must coordinate more precisely and can not move the load as easily ballistically. The different levels of trunk muscle coactivation associated with these two conditions would certainly be

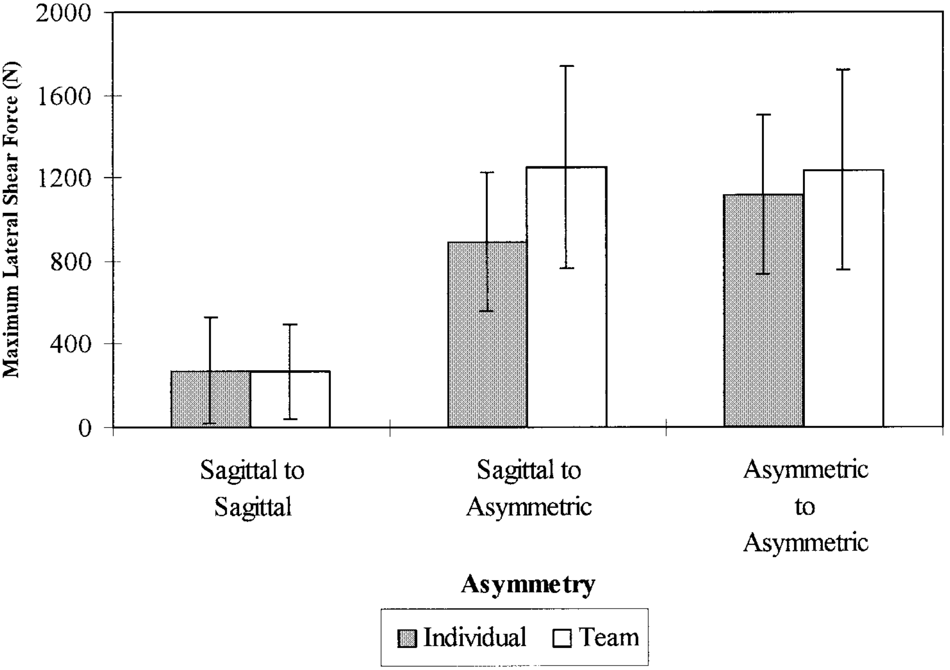

Figure 5. Maximum lateral shear force as a function of the number of lifters and asymmetry (general destination for individual).

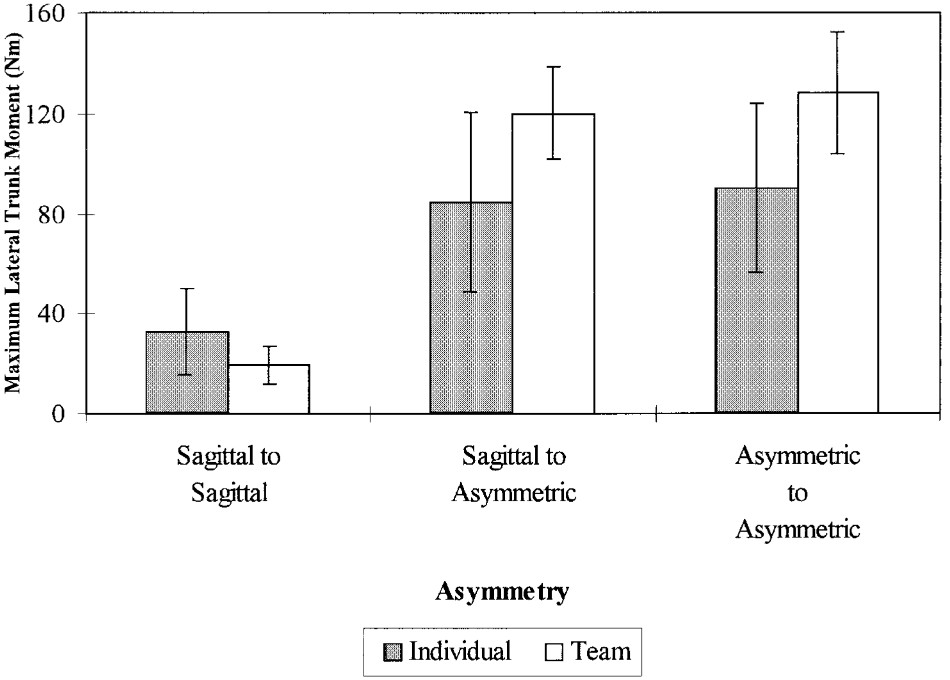

Figure 6. Maximum lateral trunk moment as a function of the number of lifters and asymmetry (general destination for individual).

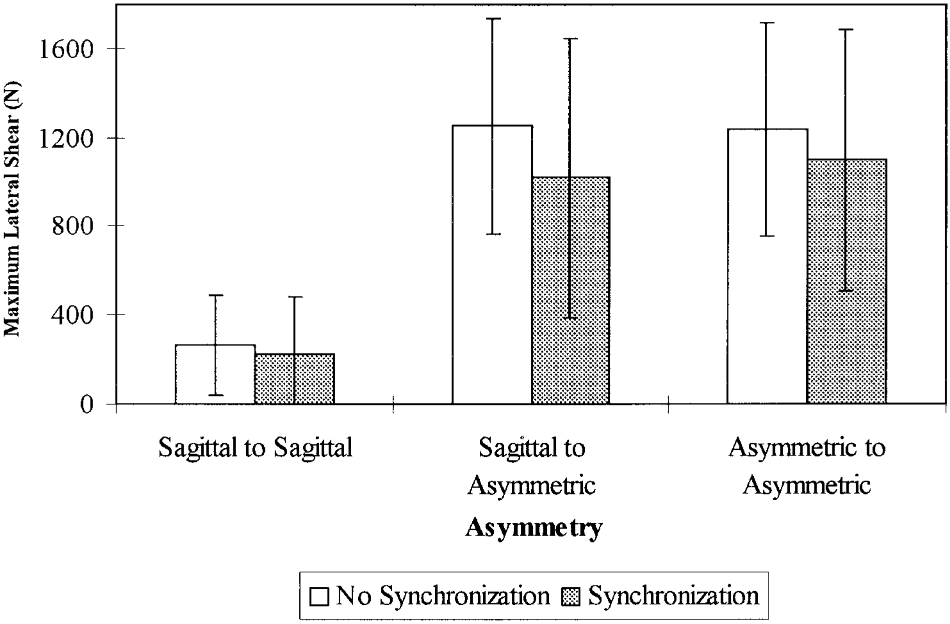

Figure 7. Maximum lateral shear force as a function of the synchronization and asymmetry.

expected to load the spine differently. Therefore, the experiment was repeated while permitting the one-person lifting conditions to be performed without the requirements of placing the load at a specific location. Instead, the load had only be placed in a general destination position.

The analyses of these experimental conditions indicated a significant reaction of spine lateral shear and compression forces to the interaction of the number of lifting team members and the lifting asymmetry conditions ($p < 0.01$). The pattern of compressive loading was indistinguishable from the previous analysis. However, the lateral shear forces imposed upon the spine changed significantly from condition to condition. Figure 5 indicates that the only significant differences between one- and two-person lifts associated with lateral shear were those involving asymmetric destinations of the load. In these cases, the one-person lifting condition always resulted in less shear loading on the spine. These differences also have biomechanical significance since the one-person lifts are below what is thought to be the tolerance limit of 1000 N for lateral shear (McGill 1996), whereas the two-person lifts exceed this tolerance limit. These lateral shear loads are generally associated with the lateral moments imposed on the spine by the task as shown in figure 6. Hence, this analysis has indicated that another factor that influences the suitability of one-versus two-person lifts is the degree to which the load must be placed accurately at the destination.

When the responses of the kinematic variables were compared with responses in the previous fixed location destination study, most of the spine loading and kinematic variables behaved very similarly. The significant differences were associated primarily with the moments and movements in the lateral and twisting dimensions ($p < 0.05$). When the interaction of task asymmetry and number of team lifters was examined, the two-person lifts resulted in less lateral velocity and twisting velocity under most conditions involving an asymmetric load destination ($p < 0.05$). In general, one person lifting (main effect) also resulted in less spine lateral shear, twisting velocity, sagittal trunk position and lateral trunk moment. Thus, it appears that the lower lateral spinal shear loads associated with one-person lifts were accomplished by minimizing lateral and twisting motions and the subsequent lateral trunk moments.

There are several other factors that should be considered which may alter the relationship between team lifting and lateral shear loads. We also hypothesize that this lateral shear trend would be enhanced if the subjects were of significantly different stature. This would probably be due to the fact that when lifting with a partner it was not possible to point the body in the direction of the load as can be done while lifting without a partner. Instead the team members must twist the torso and hips while carrying the load. In addition, previous work (Marras and Davis 1998) has indicated that asymmetric lifting is also influenced by the number of hands used in the lift and the direction of twist. Hence, the spine loading would be expected to differ as a function of which side of the box the subject supported. Furthermore, one would expect that a lateral lift performed with a partner would involve more resistance to lateral movement since it must involve a coordinated movement with the partner. This combination of events would increase the activity of the horizontally oriented muscles that would increase the lateral shear forces acting on the spine. These possible explanations for why mismatches (in stature) between subjects would affect the spinal loading tend to support the concept proposed by Rice *et al.* (1995) that the weaker person may define team lift capacity. Only future biomechanical studies, designed similar to the current study, can verify this hypothesis.

4.3. *Lift synchronization*

We also hypothesized that another factor that might affect spine loading under team lift conditions would be lift synchronization. The experiment was repeated, except that this time the team members were trained to lift synchronously. This was accomplished by providing a verbal 'count' to coordinate the actions of the two members. A practice period was provided until the team members felt that they had synchronized their movements.

When the spine loadings were evaluated under these conditions, the differences in spine compression between the asymmetry and number of lifters interaction were no longer significantly different ($p < 0.05$). The only statistically significant difference in asymmetry by team interaction involved the lateral shear force ($p < 0.05$) (figure 7). Under the asymmetric team lifting conditions the maximum lateral shear force was reduced by an average of 190 N. Little difference in spinal shear occurred in the symmetric lifts under these conditions. When the kinetic and kinematic data were evaluated for these conditions, it was found that both the lateral and sagittal trunk moments were reduced when synchronized lifting occurred. This reduction was particularly relevant since the shear forces were reduced to a level below what is considered risky. In addition, maximum shear and compression were reduced by 140 and 300 N respectively (across all conditions) when the lifts were performed synchronously.

These findings indicate that one means to mediate the increased risk associated with team lifting under the most problematic asymmetric lifting conditions would be to train the team members to lift in synchrony. The effect of this training appears to minimize the differences in the kinematic and kinetic trunk movement variables between the asymmetric lifting conditions.

4.4. *Load carrying*

Another possible source of biomechanical stress associated with one- versus two-person lifting might be associated with load carrying. Thus, the final investigation involved examination of the differences in spine loading as subjects carried a load after the lift. This was evaluated with one- compared with two-person carries.

No difference was found in spinal compression between the number of lifters for any of the lifting conditions ($p < 0.05$). However, unlike these lifting conditions, carrying a load and placing the load in a specific location by ones self resulted in greater spinal compression compared with carrying a load as a team. On average, the maximum spinal compression was reduced by 350 N during the team- compared with the one-person carry. One-person carrying also resulted in a greater sagittal moment than a two-person carrying, which appeared to help explain this increased compression.

The carrying task was also repeated under conditions that permitted the handler to place the load in a general location as opposed to a specific (fixed) location. When these data were evaluated, a change in spinal lateral shear force was observed but no change in compression or A-P shear was noted ($p < 0.05$). Under these conditions, the maximum lateral shear experienced by the one-person carrier was greatly reduced (by 420 N) compared with the two-person carrying task. The two-person carrying task was also associated with greater maximum trunk moment, twisting trunk moment, deviation in the torso twist position, deviation in lateral positions, twisting velocity, maximum lateral velocity and sagittal acceleration. Hence, the torso positions and motions were observed to involve a much greater amount of off-sagittal plane activity.

Collectively these two carrying conditions indicate that there is a trade-off in spinal loading associated with carrying that is dependent upon the final destination of the load.

When carrying a load under a one-person condition and placing the load in a specific location, the compression would be greater than when performing the task under two-person team conditions. On the other hand, spinal lateral shear would be significantly greater if a two-person team was carrying the load compared with one person carrying the load and placing it in a preferred location. It has been suggested (Shirazi-Adl *et al.* 1986) that combinations of compression and shear are associated with risk of injury, and that both factors must be considered when designing work situations. However, the percent reduction in lateral shear provides a better pay-off relative to the shear tolerance limit compared with the pay-off realized with spine compression. In addition, allowing the individual to place the box in a general position instead of a specific location would offset any difference in spine loading during team carrying of a load.

4.5. *Limitations*

An apparent paradox associated with this study resides in the fact that the asymmetric lift destination was not located at the same height as the symmetric destination. The symmetric destination was located at a point 28 cm lower than the asymmetric destination. The tasks were designed in this manner to match lifting conditions observed in military materials handling situations. To determine whether these results might be generalized over the same range, the results were examined to determine whether the peak loadings and movements occurred near these destinations. This examination revealed that all the maximum or peak values reported in this study occurred very early in the lift. Thus, these results would be minimally affected had the study been designed to observe exactly the same vertical destinations under symmetric and asymmetric lifting conditions.

In addition, it should be emphasized that these results only apply to lifting team members who have been matched in stature. We would expect that mismatching the lifting team members would exacerbate the differences in a manner similar to the asynchronous lifting conditions observed in this study.

Finally, these results must be viewed in context. Many differences between one- and two-person lifts have been identified here and many of these findings indicate that two-person lifts are more risky than one-person lifts. However, when interpreting these findings, one must remember that in these investigations two-person lifts involved lifting twice the total load compared with one-person lifts, so that the load lifted was equal under all conditions. Hence, when the load cannot be divided up into separate smaller masses, as when moving furniture or during patient lifting, one must consider the trade-off between the much greater mass supported in a one-person lift compared with the risk associated with a two-person lift. In some situations, such as patient lifting (Marras *et al.* 1998), one would be best advised to use mechanical interventions to perform the lift.

5. Conclusions

These results indicate that there are significant trade-offs associated with one- versus two-person lifting. This study has found that the preferable number of team members involved in lifting depends on many factors. In general, one person lifting is beneficial when lifting under symmetric lifting conditions. In addition, lateral shear forces may become problematic when two-person teams place a load in a specific asymmetric location compared with allowing a one-person lifter to place a load in an asymmetric ‘non-fixed’ location. Thus, precision of placement is a variable that must be considered when lifting. Next, the detrimental effects of two-person lifting can be significantly mediated, especially at asymmetric destinations, by training the lifting team to lift synchronously. Finally, a significant trade-off is associated with one- versus two-person carrying tasks. Spine compression is greater with one-person carrying, whereas lateral shear is greater with two-person carrying. The degree to which the destination of the load placement is specified also affects this trade-off.

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