BIOMECHANICAL MODELING OF ASYMMETRIC LIFTING TASKS IN CONSTRAINED LIFTING POSTURES

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Twelve subjects participated in an investigation of the biomechanical stresses of asymmetric lifting in stooped and kneeling postures. Three factors were manipulated in this study: Posture (stooped or kneeling), height of lift (35 or 70 cm), and weight of lift (15, 20, or 25 kg). Subjects were required to lift or lower a box every 10 seconds for a period of 2 minutes. Electromyography (EMG) of eight trunk muscles was collected during a lift in this period. The EMG data, normalized to maximum extension and flexion exertions in each posture, were input to a biomechanical model and used to predict compression and shear forces at the L_3 level of the lumbar spine. Results from the EMG-driven biomechanical model indicated that compression was greater when lifting to a higher shelf ($p < 0.001$), and indicated a significant interaction between posture and the weight of the lifting box ($p < 0.01$). Peak lateral shear was not significantly affected by any main effects or interactions ($p < 0.05$). Anterior shear was increased with increasing height of lift ($p < 0.001$), and also by the posture x weight interaction ($p < 0.01$). A multivariate analysis of variance (MANOVA) indicated a complex relationship for recruitment of the eight trunk muscles, with the triple interaction being significant ($p < 0.001$). The results of this investigation will be used to evaluate safe loads for lifting in these restricted postures.

INTRODUCTION

The height of an underground coal mine is generally determined by the thickness of the coal seam. In several cases, the coal seam of a mine may be less than 48" high. Such mines are often called "low-seam" coal mines. Workers in these mines often have to lift heavy materials in restricted postures (usually stooped or kneeling). There is reason to believe these postures result in significant compressive and shear loading on the lumbar spine.

Previous Bureau of Mines research has described the psychophysical lifting capacity, metabolic demands, and electromyography (EMG) of trunk muscles when performing tasks in restricted postures (Gallagher, *et al.*, 1988; Gallagher and Unger, *in press*). Other investigators have researched the intraabdominal pressure associated with lifting in these postures (Davis and Troup, 1966; Ridd, 1981; Sims and Graveling, 1988). However, little research has been performed estimating the internal forces on the lumbar spine due to trunk muscle contraction in these postures. Marras and Sommerich (1990) recently described a biomechanical model driven by trunk muscle EMG that allows estimates of forces acting on the lumbar spine. A paper describing the results of this model's estimates of forces during symmetric lifting in restricted postures can be found elsewhere (Gallagher, *et al.*, 1990). The purpose of the current investigation was to estimate the internal forces acting on the lumbar spine during asymmetric lifting tasks in stooped and kneeling postures.

METHOD

Subjects

Twelve healthy male subjects (*M* = 35.7 years of age ± 6.8 S.D.) volunteered to participate in a study examining the biomechanics of asymmetric lifting in restricted postures. Nine of the subjects were experienced underground miners, while three of the subjects were volunteers from the U.S. Bureau of Mines. All participants operated under terms of informed consent.

Experimental procedure

Three independent variables were manipulated in this experiment -- posture (P) for the lift (stooped or kneeling), height (H) to which the box was lifted (35 or 70 cm), and weight (W) of the lifting box (15, 20, or 25 kg). A within subjects repeated measures design was employed. EMGs of eight trunk muscles (l. and r. erectores spinae, latissimus dorsi, external oblique, and rectus abdominis) were collected during lifting tasks, and were later digitized and input to a dynamic biomechanical model (Marras and Sommerich, 1990). The model output included estimates of compression, anterior-posterior shear and right lateral shear (at the L_3 level of the lumbar spine), as well as torques about the X, Y, and Z axes, using the coordinate system described by Schultz and Andersson (1981). In addition, the model produced estimates of muscle forces for the eight trunk muscles. The assumption was made that the maximum stress that could be exerted by a muscle was 50 N/cm^2 (Reid and Costigan, 1987). Estimates of the cross-sectional areas of trunk muscles were obtained through anthropometric measurements, as described by Schultz, *et al.* (1982). All dependent variables except muscle forces were analyzed using 2 x 2 x 3 (P x H x W) analyses of variance (ANOVA). The data on muscle forces were subjected to a 2 x 2 x 3 (P x H x W) multivariate analysis of variance (MANOVA). Critical alpha levels were .05 for all statistical tests.

The lifting tasks were performed under a 1.2 m roof that restricted the subject's posture. An aluminum lifting box (50.8 x 33.0 x 17.8 cm) with two covered compartments was used to perform the lifting tasks. The subject performed a series of twelve asymmetric lifting and lowering tasks in a counterbalanced order. The subject was required to lift or lower the box to the appropriate height every 10 seconds for a period of 2 minutes. EMG data were collected during the third lift of this sequence.

RESULTS

Table 1 summarizes significant main effects and interactions for the dependent variables (outputs from the biomechanical model) in this investigation. Table 2 contains average model estimates of compression, shear, and torque for each of the experimental conditions.

Table 1.-- Summary of significant main effects and interactions for all dependent variables.

	Pos	Ht	Wt	PxH	PxW	HxW	PxHxW
Peak Compression	*	***	***		**		
Peak Lat. Shear	.067		.091		.080		
Peak Ant. Shear	.100	***	***		**	.075	
Peak X Torque	*	**	***				
Peak Y Torque							
Peak Z Torque	**			***	*		
Peak Mus. Force	***	***	***	**	***	***	***
Ave. Compression	**	***	***		*		
Ave. Lat. Shear							
Ave. Ant. Shear		***	***		*		
Ave. X Torque	***	**	***				
Ave. Y Torque	*	.090					
Ave. Z Torque	*	*		**	*		
Ave. Mus. Force	**	**	***	**	***	***	***

* $p < 0.050$
** $p < 0.010$
*** $p < 0.001$

Table 2.-- Model estimates of compression, shear, and torque for all experimental conditions. Values represent the mean for all 12 subjects. Numbers in parentheses represent the standard deviation.

	Compression	A-P Shear	R-L Shear	X Torque	Y Torque	Z Torque
Kneeling 35 cm, 15 kg	1599.6 (383.4)	187.3 (86.0)	21.9 (16.0)	56.5 (18.5)	22.0 (11.2)	5.9 (5.2)
Kneeling 35 cm, 20 kg	1788.8 (345.7)	207.5 (88.0)	20.0 (16.7)	62.9 (20.0)	24.7 (11.2)	6.2 (4.3)
Kneeling 35 cm, 25 kg	2114.2 (374.2)	275.2 (144.8)	22.3 (16.4)	75.6 (21.1)	25.4 (12.9)	9.4 (4.8)
Kneeling 70 cm, 15 kg	1942.1 (378.6)	244.5 (114.2)	24.0 (17.2)	69.4 (18.0)	22.3 (10.1)	8.0 (5.5)
Kneeling 70 cm, 20 kg	2188.2 (322.8)	262.5 (98.3)	24.4 (16.0)	78.2 (17.0)	24.9 (11.1)	8.9 (4.9)
Kneeling 70 cm, 25 kg	2560.2 (343.5)	360.1 (150.9)	23.6 (18.5)	89.4 (17.7)	22.1 (9.8)	11.1 (6.3)
Stooped 35 cm, 15 kg	1375.0 (450.9)	159.8 (75.8)	24.8 (17.1)	44.8 (23.0)	13.6 (9.3)	6.6 (4.3)
Stooped 35 cm, 20 kg	1521.6 (502.0)	185.9 (75.0)	27.1 (14.4)	49.2 (25.2)	13.5 (8.8)	9.4 (5.3)
Stooped 35 cm, 25 kg	1719.3 (433.3)	194.5 (66.4)	23.4 (11.5)	58.2 (21.0)	15.9 (9.7)	9.4 (4.8)
Stooped 70 cm, 15 kg	1593.5 (507.6)	208.5 (63.7)	27.7 (16.6)	49.7 (22.9)	15.5 (10.4)	12.8 (9.0)
Stooped 70 cm, 20 kg	1810.1 (549.6)	244.3 (99.6)	25.7 (13.9)	57.3 (27.3)	17.5 (12.7)	13.0 (7.7)
Stooped 70 cm, 25 kg	1974.3 (600.5)	279.6 (97.0)	31.4 (21.2)	64.3 (31.6)	20.2 (10.8)	17.1 (9.0)

Compression

As can be seen in this Table 1, there was a significant PxW interaction on compression. Table 2 shows that compression increased at a higher rate for kneeling compared to stooping; however, kneeling compression was always higher than that observed when stooped. The height of lift had the expected effect on compression (i.e., lifting to a higher shelf increased compression).

Shear Forces

Lateral shear was not significantly affected by any independent variables. However, peak anterior shear was significantly affected by lifting height, as well as by the PxW interaction. Examination of Table 2 shows that anterior shear was increased with increasing height of lift, while anterior shear increased at a higher rate in the kneeling posture, compared to stooped.

Muscle Forces

The MANOVA on muscle forces for the eight trunk muscles studied indicated a complicated recruitment pattern due to the changing conditions. The P x H x W interaction achieved significance at the 0.001 level. Figure 1 illustrates the average over the 12 subjects of peak EMG activity during lifts for the eight trunk muscles studied for all experimental conditions. These EMG data were normalized to maximum exertions for each of the subjects, using procedures described by Marras (1987).

DISCUSSION

Compared to a previously reported study on symmetric lifting in restricted postures (Gallagher, et al., 1990), many of the internal responses to asymmetric lifting were affected by interactions of the independent variables. For example, both compression and anterior shear were significantly affected by the PxW interaction. This phenomenon was not observed in the symmetric lifting study. Several similarities between the two studies can be noted, however. For example, in both studies compression was consistently higher in the kneeling posture when compared to the stooped posture. This is primarily the result of increased erectores spinae activity when lifting in the kneeling position.

In the study examining symmetric lifting (Gallagher, *et al.,* 1990), peak lateral shear was found to be significantly greater in the stooped posture. In contrast, the present study showed a trend (non-significant) towards greater peak lateral shear in the kneeling posture. This reflects a difference in recruitment of the latissimus dorsi muscles in these two postures according to the symmetry of the lifting task. As with the previous study, anterior shear was generally greater in the stooped posture, indicating greater activity of the abdominal obliques in this position.

Another similarity of the two studies was the complex recruitment pattern of the trunk musculature for the treatments studied. However, certain observations can be made with regard to trunk muscle activity. For example, the activity of the latissimus dorsi were higher in the stooped posture than when kneeling. However, increased erectores spinae activity was consistently demonstrated in the kneeling posture. The rectus abdominis were slightly more active in the stooped posture.

While the current model appears to give a good picture of the muscular loading on the spine, it is worth noting that this model is as yet unable to address other biomechanical factors that may be responsible for production of low back pain. For instance, in the stooped posture investigated here, a large portion of the restorative moment to maintain the position of the trunk is provided through the muscle-sparing action of the posterior ligaments (Gracovetsky and Farfan, 1986). The strain on these ligaments is apt to be quite considerable, but unfortunately remains difficult to quantify, and is not addressed by the current model.

The data reported in this study will assist in the development of recommendations for manual lifting tasks in the underground mining environment. The model estimates of compression will be compared to known compression tolerance limits of the spine, and recommended load limits will be designed so that these tolerance limits are not exceeded.

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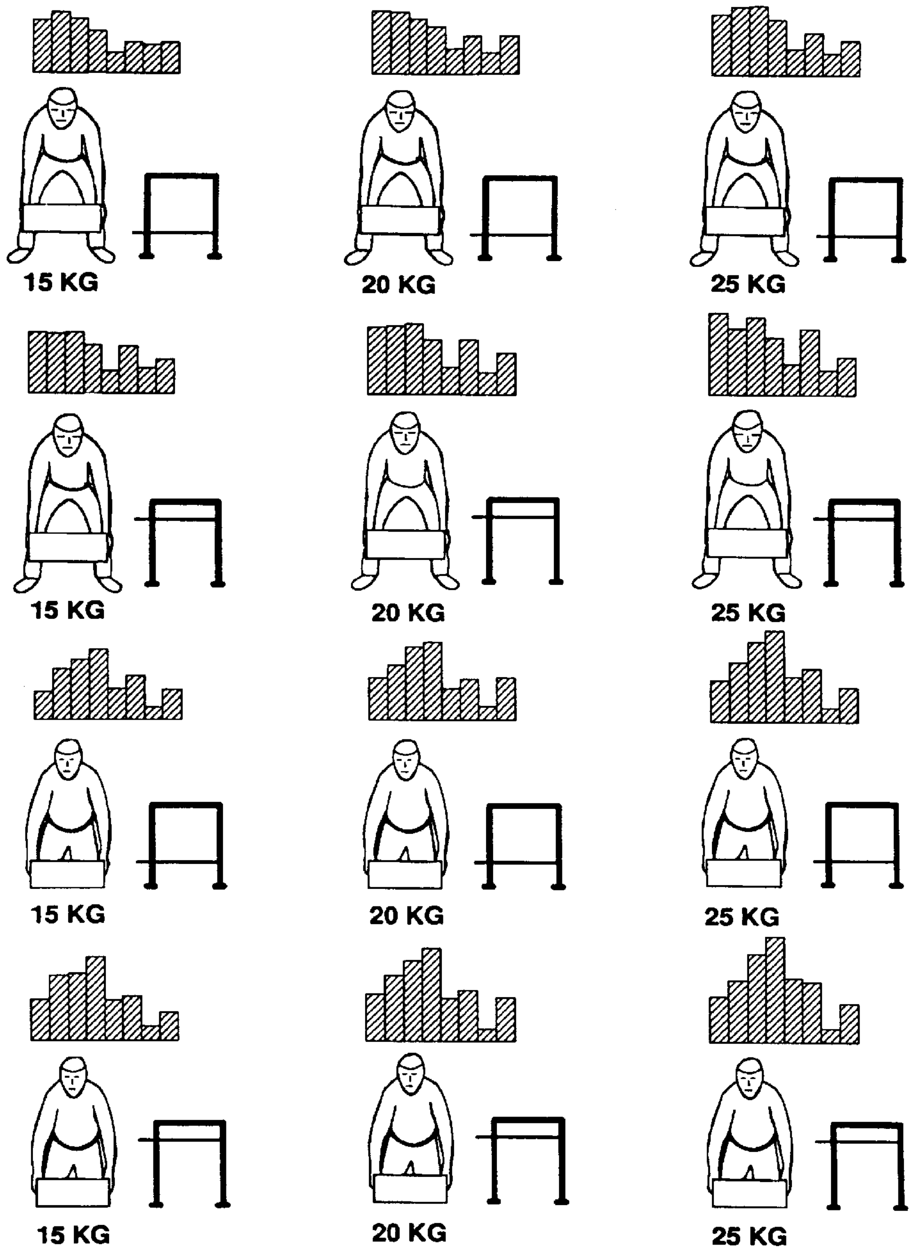

Figure 1. Normalized peak EMG for each experimental condition. From left to right, muscles represented in histograms are l. and r. latissimus dorsi, l. and r. erectores spinae, l. and r. external obliques, and l. and r. rectus abdominis.