LIFTING IN STOOPED AND KNEELING POSTURES: EFFECTS ON LIFTING CAPACITY, METABOLIC COSTS, AND ELECTROMYOGRAPHY OF EIGHT TRUNK MUSCLES

Sean Gallagher *

U.S. Department of the Interior, Bureau of Mines, Pittsburgh Research Center, Pittsburgh, PA 15236 (U.S.A.)

William S. Marras

Department of Industrial and Systems Engineering, The Ohio State University, Columbus, OH 43210 (U.S.A.)

and Thomas G. Bobick

U.S. Department of the Interior, Bureau of Mines, Pittsburgh Research Center, Pittsburgh, PA 15236 (U.S.A.)

ABSTRACT

Twelve healthy, experienced underground coal miners performed lifting capacity tests in stooped and kneeling postures using a modified psychophysical procedure. Subjects adjusted weight in a lifting box to the maximum they could handle without undue fatigue in an asymmetric lifting task. Lifting periods were 20 min in duration and the frequency was 10 lifts/min. Tests were performed under a 48-in. roof that restricted the subject's posture. Psychophysical, physiological, and biomechanical dependent measures included the maximum acceptable weight of lift (MAWL), heart rate (HR), rate of oxygen consumption ($\dot{V}O_2$), ventilation volume rate ($\dot{V}_E$), respiratory exchange ratio (R), and integrated electromyography (EMG) of eight trunk muscles. Results indicated that the MAWL was significantly lower when kneeling than when stooped ($p < 0.05$). Furthermore, metabolic demands were greater in terms of HR ($p < 0.005$) and VO_2 ($p < 0.05$) when kneeling. Left and right erectores spinae muscles exhibited increased EMG activity in the kneeling posture ($p < 0.001$). It was concluded that psychophysical lifting capacity is decreased, while the metabolic stress and internal load on the spine are increased, in the kneeling posture. Results of this Bureau of Mines study indicate that it may be advisable to reduce the weight of materials that are handled repetitively in the kneeling posture.

INTRODUCTION

Underground miners who work in low-seam coal mines (≤ 48-in. roof height) often lift heavy

* Please address reprint requests to: Sean Gallagher, U.S. Bureau of Mines, P.O. Box 18070, Cochrans Mill Rd., Pittsburgh, PA 15236, U.S.A.

materials in severely restricted work postures. Two postures that are most often used during manual materials handling (MMH) activities in low-seam mines are stooped and on two knees (Bobick, 1987). Both postures are the result of a restricted working environment, and cause considerable stress to the spine. Lifting in such postures may help to explain the high incidence of low-back pain in the mining industry (MacDonald et al., 1984). For example, the stooped posture substantially increases the moment (and thus the force) experienced by the intervertebral disks of the spine (Nachemson, 1976; Cailliet, 1981). The kneeling posture, on the other hand, often causes the miner to use a twisting motion of the trunk to accomplish a lift, primarily due to the restricted mobility experienced when working on one's knees. The torsional load experienced by the spine when the trunk is twisted is also recognized as a significant mode of injury to the lumbar spine (Liu et al., 1985; Gracovetsky and Farfan, 1986). Therefore, the postures most often used to lift materials in the low-coal mine environment cause the miner to perform what are generally regarded as the two worst actions in terms of causing low-back pain: bending and twisting (Macnab, 1983; Krämer, 1981; Liu et al., 1985; Gracovetsky and Farfan, 1986).

Three approaches have traditionally been used to determine the stresses imposed on workers performing MMH tasks: psychophysical, physiological, and biomechanical. Each of these methods has both advantages and limitations. For instance, the psychophysical approach of determining lifting capacity has been shown to permit realistic simulation of industrial work situations and results of these tests are very reproducible (Snook, 1985a). However, this method is not objective because it relies on the assumption that people are capable of determining workloads that are safe for them. The physiological method is useful in determining the metabolic demands on the body due to the lifting task, and can provide an indication of muscular fatigue (U.S. Department of Health and Human Services, 1981; Jorgensen, 1985). However, this technique may neglect the biomechanical stresses of lifting. Finally, the biomechanical method can estimate the forces imposed on the lumbar spine, but is not sensitive to factors such as muscular fatigue (Ayoub et al., 1983). Therefore, it seems reasonable when examining materials-handling tasks to utilize all three methods to better quantify the combination of stresses inherent in a lifting task.

Many researchers have utilized one or more of these techniques to develop lifting limits for materials handling in unrestricted work postures (Snook et al., 1970; Ayoub et al., 1979; U.S. Department of Health and Human Services, 1981; Mital, 1984). However, there exists a comparative void in research that has studied the psychophysical, physiological, and biomechanical stresses associated with lifting materials in constrained work postures (Gallagher, 1987). The present investigation was performed in order to quantify the subjective lifting capacity of underground miners in stooped and kneeling postures, and to assess the metabolic costs and biomechanical consequences of lifting in these postures.

METHOD

Subjects

Twelve healthy male underground miners (*M* = 36 years of age ±8 S.D.) participated in a study examining the effects of posture on lifting capacity. Subjects were paid volunteers from four low-seam coal mines in Ohio and Pennsylvania and were experienced with handling materials in restricted work postures. All participants received a thorough physical examination and graded exercise tolerance test (American College of Sports Medicine, 1980) to insure good health, and only candidates who had no history of a lost-time back injury were accepted for the study. Thus, these subjects represented "survivors" of the under-

TABLE 1

Selected physical characteristics of the mining test subjects in this study compared to anthropometric data on male underground miners collected by Texas Tech University (Ayoub et al., 1981)

Measurement	U.S.B.M. low-coal miners			Texas Tech low-coal miners		
	Mean	S.D.	*N*	Mean	S.D.	*N*
Age (years)	36	8	12	35	11	135
Weight (kg)	83.8	13.9	12	81.9	16.8	132
Stature (cm)	173.8	6.7	12	174.4	6.5	136

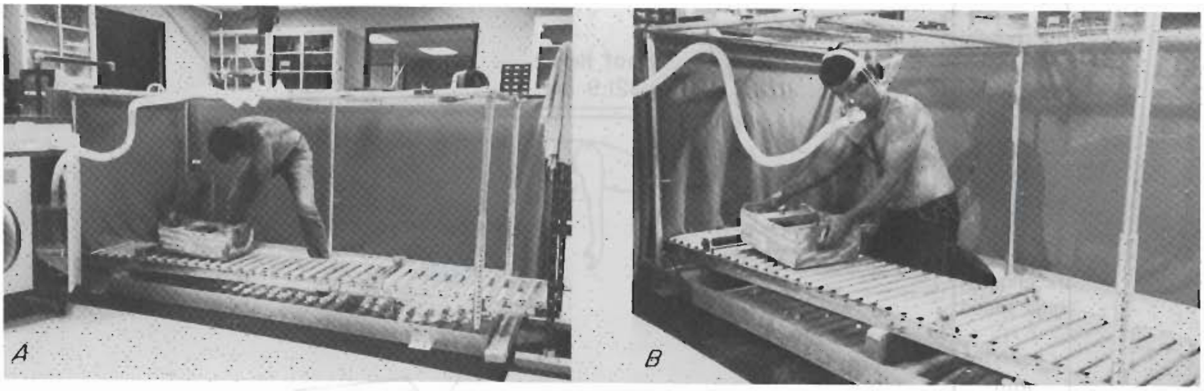

Fig. 1. Subject performing lifting tasks in (A) stooped, and (B) kneeling postures.

ground mining environment. Subjects were advised of the nature of the investigation and signed an informed consent form before participating. Five of the 12 subjects in this study were cigarette smokers. Table 1 presents physical characteristics of the present subject population, which are compared with data collected by Ayoub et al. (1981) of male low-coal miners from 17 underground mines in three eastern coal-mining states. Comparisons of the two samples using the Behrens–Fisher statistic indicate that neither age ($t'_{\pm 0.025,15} = 0.401$, $p = 0.694$), weight ($t'_{\pm 0.025,13} = 0.445$, $p = 0.663$), nor stature ($t'_{\pm 0.025,12} = -0.298$, $p = 0.771$) were significantly different.

Experimental design

The independent variable in this investigation was the posture assumed during the lifting task: stooped or kneeling. Figure 1 illustrates the two postures used in this study. The dependent measure for the psychophysical portion consisted of the average subjectively determined weight chosen for two test conditions in each posture. Physiological dependent measures included heart rate (HR), oxygen utilization ($\dot{V}O_2$), ventilation volume ($\dot{V}_E$), and the respiratory exchange ratio (R). Integrated electromyographic (EMG) data were collected from eight trunk muscles in six of the subjects and served as the dependent variables for the biomechanical portion of the experiment.

Apparatus

A schematic of the equipment used in this experiment is shown in Fig. 2. The weight of the lifting box was determined using an Arlyn * Model 300-D digital scale (sensitivity: ± 0.045 kg). Heart rate was obtained using a Beckman Dynograph Recorder, Model 511-A. Oxygen consumption, ventilation volume, and respiratory exchange ratio values were acquired using a Beckman Metabolic Measurement Cart I. An electromyographic data collection system designed and built by Ohio State University was used in this study. Integrated EMG data were collected using surface electrodes placed over selected muscles of interest. The eight muscles studied in these subjects were the left and right erectores spinae, latissimus dorsi, external oblique, and rectus abdominis. EMG signals were boosted via belt-wearable preamps and were transferred to the integrator/amplifier through shielded cables. In order to ensure a good quality signal, the muscle activity was monitored prior to each test on an oscilloscope. Each EMG signal was rectified and averaged using a root mean square (RMS) procedure. The integrator constant was 500 ms, and the EMG data were conditioned using 80 Hz high-pass and 1000 Hz low-pass filters. An ISAAC 2000 data acquisition system was used for on-line collection and the data were stored on a microcomputer for subsequent data analysis. In both postures it was assumed that the back was in a static position for the purposes of the EMG analysis. Integrated EMG data were normalized with respect to the maximum EMG obtained for each muscle during maximum trunk flexion and exten-

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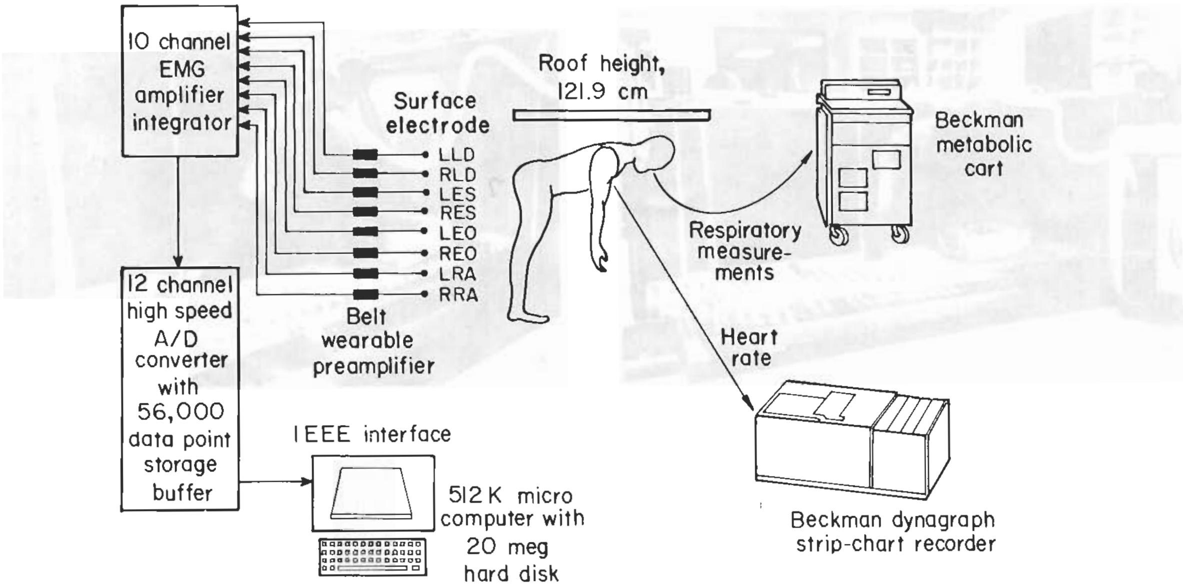

Fig. 2. Schematic of apparatus used for data collection. Note: LLD = left latissimus dorsi, RLD = right latissimus dorsi, LES = left erector spinae, RES = right erector spinae, LEO = left external oblique, REO = right external oblique, LRA = left rectus abdominis, RRA = right rectus abdominis.

sion exertions, according to procedures described by Marras (1987).

Experimental task

Subjects were asked to adjust the weight in a 50.8 × 33.0 × 17.8 cm (20 × 13 × 7 in.) lifting box according to the subject's own estimate of lifting capacity for each posture. The lifting tasks were performed under an adjustable-height mine simulator that restricted the subject's posture. The height of the simulator was set at 121.9 cm (48 in.) for this study. Lifting instructions were given to the subject before the experiment started in accordance with Snook and Irvine (1967), as modified by Snook (1985b). In this study, the subjects were told to adjust the weight in the box so the load could be handled for 20 min and to assume that this 20 min of lifting would have to be performed four times during a workday. It should be noted that multiple psychophysical trials to establish a consistent and repeatable load were not possible in this experiment; thus, the subjects provided a one-time estimate of their lifting capacity in the two postures.

The subject lifted the box at a frequency of 10 per min for two 20-min periods in each posture. One lifting period started with a heavy box, weighing approximately 43.1 kg (95 lb), and the other with a light box, weighing approximately 11.3 kg (25 lb), to control for bias due to the initial starting weight of the box. The frequency of lifting was controlled using a computer-generated voice prompt. Subjects were unaware of the weight they were lifting. The lifting box had two covered compartments and initial starting weight above and below these compartments was randomly varied. The average subjectively determined weight for the two tests in each posture was taken as the maximum acceptable weight of lift (MAWL) for that posture. Heart rate was collected during the last 10 s of every minute. The final 15 heart rate values were averaged and taken as the mean HR for that test condition. Respiratory measurements were obtained approximately every 30 s during the last 5 min of each lifting period, and were averaged by the number of values obtained during this period. Integrated EMG data were collected from six subjects at a rate of 100 Hz for a period of 3 s during a lift at minute 2 and minute 18 of each lifting period. A 10-min rest break was provided between tests so that subjects could rest and attend to personal needs. Test conditions were randomized and presented in a counterbalanced fashion.

Data treatment

The results of data for lifting capacity tests in kneeling and stooped postures (along with the associated metabolic demands) were analyzed using an analysis of variance with repeated measures statistical package (Games et al., 1980). Normalized maximum and mean integrated EMG data were analyzed using a $2 \times 2 \times 2$ (posture $\times$ time $\times$ initial box weight) multivariate analysis of variance (MANOVA). Significant MANOVA results were followed by a discriminant function analysis and by univariate F-tests to determine the individual muscles responsible for the significant MANOVA result (Borgen and Seling, 1978). Due to the asymmetric nature of the lifting task, separate MANOVAs were performed for both mean and maximum EMG activity to determine the relative contribution of muscles on either side of the body in both postures. Significant results for these analyses were followed using the post hoc tests described above. Critical alpha levels were 0.05 in all cases.

RESULTS

Maximum acceptable weights of lift

The results of the MAWL tests and associated physiological data are presented in Table 2. This table shows that the kneeling MAWL for the twelve mining subjects was significantly lower than the stooped MAWL ($F_{1,11} = 7.801$, $p < 0.05$). On the average, these miners lifted 30.9 kg (68.0 lb) in the stooped posture and 26.8 kg (59.1 lb) when kneeling. Two of the subjects lifted slightly greater weight in the kneeling posture; however, the majority were able to handle more weight in the stooped position.

TABLE 2

Results of maximum acceptable weight of lift (MAWL) test for all underground miners ($N = 12$)

	Stooped	Kneeling	Significance
MAWL (kg)	30.9	26.8	$p < 0.05$
	($\pm$4.1)	($\pm$5.0)	
HR (bpm)	123	137	$p < 0.005$
	($\pm$12)	($\pm$12)	
$\dot{V}O_2$	14.9	16.5	$p < 0.05$
(mL/kg/min)	($\pm$2.9)	($\pm$3.9)	
$\dot{V}_E$ (L/min)	32.7	35.6	n.s.
	($\pm$6.1)	($\pm$6.7)	($p = 0.077$)
R	0.83	0.81	n.s.
	($\pm$0.09)	($\pm$0.09)	($p = 0.404$)

Note: bpm = beats per minute; mL/kg/min = milliliters per kilogram body weight per minute; n.s. = not significant; numbers in parentheses represent the standard deviation.

Physiological data

Despite the fact that less weight was lifted in the kneeling posture, the physiological demands of lifting in this posture were higher than in the stooped posture for both heart rate ($F_{1,11} = 13.215$, $p < 0.005$), and oxygen consumption ($F_{1,11} = 5.547$, $p < 0.05$). Neither ventilation volume ($F_{1,11} = 3.814$, $p = 0.077$) nor respiratory exchange ratio ($F_{1,11} = 0.754$, $p = 0.404$) were significantly affected by the posture assumed during lifting. Absolute oxygen consumption values were also higher in the kneeling posture (mean = 1.41 L/min $\pm$ 0.46 S.D.) than when stooped (mean = 1.30 L/min $\pm$ 0.37 S.D.). It should be noted that relative metabolic cost of lifting (i.e., the metabolic cost per kg of weight lifted) is also increased in the kneeling posture.

Electromyography

The MANOVA for both maximum ($F_{8,26} = 12.622$, $p < 0.001$) and mean ($F_{8,25} = 6.037$, $p < 0.001$) EMG activity during the lifting tasks demonstrated significant main effects due to posture. Figures 3 and 4 contain the results of the maximum and mean integrated EMG data collected during this study, respectively. The prominent characteristic of these figures is that the right and left erectores spinae demonstrated increased activity in the kneeling posture compared to stooped. Tables 3 and 4 present the pooled within-groups correlation matrices for maximum and mean EMG activity, respectively. These tables show many significant intercorrelations between the eight trunk muscles studied for both maximum and mean EMG data. Generally stated, the activity of back muscles seem to be more highly correlated with the activity of other back muscles; activity of the abdominals also tended to be intercorrelated.

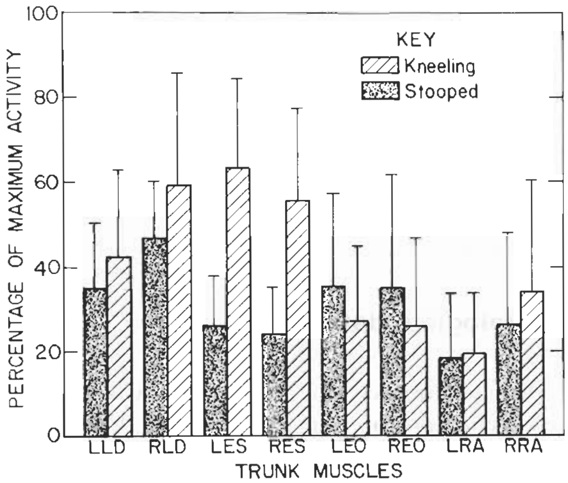

Fig. 3. Results of the maximum EMG data in the stooped and kneeling lifting tasks (mean ± S.D.). Note: Refer to Fig. 2 for muscle abbreviations.

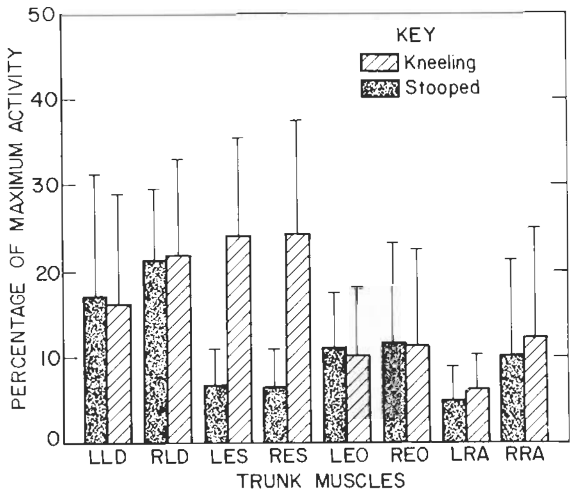

Fig. 4. Results of the mean EMG data in the stooped and kneeling lifting tasks (mean ± S.D.). Note: Refer to Fig. 2 for muscle abbreviations.

TABLE 3

Pooled within-groups correlation matrix for maximum integrated EMG data

	LLD	RLD	LES	RES	LEO	REO	LRA	RRA
LLD	1.00							
RLD	0.43 [b]	1.00						
LES	0.31	0.38 [a]	1.00					
RES	0.44 [b]	0.59 [c]	0.84 [c]	1.00				
LEO	−0.11	0.18	0.44 [b]	0.49 [b]	1.00			
REO	0.21	0.26	0.25	0.28	0.31	1.00		
LRA	0.10	0.14	−0.01	0.07	0.38 [a]	0.01	1.00	
RRA	−0.12	−0.12	0.22	0.4	0.44 [b]	0.19	0.04	1.00

Note: $N = 40$. Refer to Fig. 2 for muscle abbreviations.
[a] $p < 0.05$, [b] $p < 0.01$, [c] $p < 0.001$.

TABLE 4

Pooled within-groups correlation matrix for mean integrated EMG data

	LLD	RLD	LES	RES	LEO	REO	LRA	RRA
LLD	1.00							
RLD	0.44 [b]	1.00						
LES	0.16	0.27	1.00					
RES	0.21	0.48 [b]	0.79 [c]	1.00				
LEO	0.34 [a]	0.15	0.41 [b]	0.26	1.00			
REO	0.17	0.14	0.07	0.03	0.75 [c]	1.00		
LRA	0.34 [a]	0.07	0.13	0.07	0.41 [b]	0.24	1.00	
RRA	−0.13	−0.29	0.12	−0.06	0.28	0.37 [a]	−0.04	1.00

Note: $N = 40$. Refer to Fig. 2 for muscle abbreviations.
[a] $p < 0.05$, [b] $p < 0.01$, [c] $p < 0.001$.

TABLE 5

Results of separate discriminant analyses for maximum and mean EMG data

Discriminant function	Percent variance	Canonical correlation	Significance of discriminant	
			χ^2	p
Maximum EMG				
Function 1	100.0	0.87	51.9	0.001
Mean EMG				
Function 1	100.0	0.80	36.7	0.001

However, several significant correlations also exist between back and abdominal muscles.

Results of the discriminant analyses for both maximum and mean EMG are contained in Table 5. One discriminant function was extracted from the discriminant analysis of the normalized maximum EMG data using posture as a grouping variable. Similarly, the discriminant analysis of the normalized mean EMG data produced a single discriminating function to distinguish between postures. Results of both discriminant analyses indicate that the both maximum and mean EMG data are differentiated along a single underlying dimension. Classification results reveal that 97.6% and 90.2% of cases were correctly classified by the discriminant functions for maximum and mean EMG activity, respectively. Table 6 provides the discriminant structure matrices for both maximum and mean integrated EMG discriminant functions; findings indicate that the left and right erectores spinae correlate most highly with the functions used to discriminate between stooped and kneeling lifting postures.

When multivariate data are separated along a single dimension, univariate ANOVA has been found to adequately handle the follow-up analyses to MANOVA (Borgen and Seling, 1978). Therefore, the results of univariate ANOVA F ratios

TABLE 6

Discriminant structure matrices for normalized maximum and mean EMG activity. Values are pooled within-groups correlations between discriminating variables and canonical discriminant functions

Muscle	Discriminant	
	Max EMG Function 1	Mean EMG Function 1
Left erector spinae	0.64	0.80
Right erector spinae	0.52	0.74
Right latissimus dorsi	0.27	0.02
Left external oblique	−0.16	−0.09
Right rectus abdominis	0.10	0.12
Left latissimus dorsi	0.10	−0.13
Right external oblique	−0.05	−0.3
Left rectus abdominis	−0.01	−0.12

for the EMG data are provided in Table 7. Results of this analysis agree with that of the discriminant analysis; the left and right erectores spinae are the muscles primarily responsible for significant MANOVA results in analysis of maximum and mean integrated EMG. Both muscles exhibit significantly increased activity in the kneeling posture. Neither the initial box weight (heavy or light) nor time of EMG data acquisition (i.e., minute 2 or minute 18 of the test) had a significant effect on the EMG activity of any trunk muscles studied ($p > 0.05$).

Results of the separate MANOVA on maximum EMG activity for asymmetric muscle activity showed significant main effects due to left/right muscle side in the kneeling posture ($F_{4,34} = 5.269$, $p < 0.005$), but not in the stooped posture ($p > 0.05$). Results of the discriminant structure matrix are given in Table 8; findings indicate that the latissimus dorsi and rectus abdominis correlated highly with the function separating left and right integrated EMG activity. These muscles apparently help to control asym-

TABLE 7

Univariate ANOVA F-ratios for differences in maximum and mean EMG activity between stooped and kneeling postures

	Trunk Muscle							
	LLD	RLD	LES	RES	LEO	REO	LRA	RRA
F (Maximum EMG)	0.7	2.2	42.7 [a]	28.4 [a]	3.5	1.2	0.0	0.9
F (Mean EMG)	0.1	0.0	35.4 [a]	30.1 [a]	0.9	1.3	0.3	0.4

Note: d.f. = 1,33 for maximum EMG; d.f. = 1,32 for mean EMG. See Fig. 2 for muscle abbreviations.

[a] F significant at 0.001 level.

TABLE 8

Discriminant structure matrix for asymmetric maximum EMG activity in the kneeling posture

Muscle	Discriminant function
Latissimus dorsi	0.50
Rectus abdominis	0.45
Erectores spinae	−0.22
External oblique	−0.02

metric movements in the kneeling posture. Univariate *F*-tests for maximum EMG activity in the kneeling posture indicated that the right latissimus dorsi exhibited significantly greater peak EMG activity than the left ($F_{1,37} = 5.808$, $p < 0.05$), and that the right rectus abdominis also exhibited increased EMG activity as compared to the left ($F_{1,37} = 4.551$, $p < 0.05$). The MANOVA for asymmetric mean EMG activity failed to demonstrate significant main effects due to right versus left muscle activity in either the stooped or kneeling postures ($p > 0.05$).

DISCUSSION

Maximum acceptable weight of lift

Results of the psychophysical tests indicate that the lifting capacity of the test sample was significantly decreased in the kneeling posture as opposed to stooped at a frequency of 10 lifts per minute. The difference in lifting capacity may be due to the fact that fewer muscles can be recruited to perform the lift when kneeling. It is apparent that the large, powerful muscle groups of the legs are not able to contribute a great deal of useful force when lifting in the kneeling posture. This means that the work of lifting must be performed primarily by the muscles of the upper body, particularly shoulder and arm muscles and muscles associated with extension of the vertebral column. The back muscles would be expected to provide a substantial increase in force output to execute the lift.

In comparison with other asymmetric lifting studies, the maximum acceptable weights of lift reported in this study, while in the general range reported by others (Asfour et al., 1984; Garg and Badger, 1986; Mital and Fard, 1986), tend toward the high end. There may be several reasons why this is the case. First of all, the subjects used in this study were experienced miners, whereas many previous lifting studies have drawn test samples from populations of college students. Secondly, the vertical distance of lift required of the present subjects was considerably less in this study than in other asymmetric lifting studies. The height of lift by the present subjects was in the neighborhood of 10–20 cm; most other asymmetric lifting studies have required lifts of approximately 70 cm. In addition, the subjects in this study were instructed to select the amount of weight that could be lifted for a 20-min period, without extrapolating to a longer period of lifting. These instructions were given to reflect the fact that materials-handling tasks in underground mines are much more sporadic than those found in most other industries (Ayoub et al., 1981). Finally, as mentioned previously, this was a one-time estimate of lifting capacity, which may account for higher subjective MAWL appraisals.

Physiological responses

The physiological responses to lifting in the kneeling posture were significantly greater than in the stooped posture, despite the fact that less weight was lifted when kneeling. The increased metabolic demands of lifting in the kneeling posture may be another factor that limits the psychophysically determined lifting capacity in this position. One reason for the increased metabolic demands of lifting in this posture may be the increased activity of the erectores spinae muscles described earlier. Previous research has shown that if a smaller muscle mass is used to accomplish an equivalent workload, the heart rate and oxygen uptake adjustment by the body will be increased (Stegemann, 1981). The increased metabolic cost of lifting when kneeling indicates that the onset of fatigue may be more rapid when working in this posture. The oxygen consumption required of the subjects to perform lifting tasks when stooped appears to be in line with that reported by others relative to the weight and frequency of lift (Asfour et al., 1984; Mital and Fard, 1986); the oxygen consumption is somewhat higher in the kneeling posture than would be expected for the weight lifted at this frequency.

Electromyography

Analysis of the integrated EMG activity of the trunk muscles appears to confirm that the erectores spinae are called upon to provide a larger component of the lifting force in the kneeling posture than when lifting in the stooped position. This finding leads one to speculate that the compressive load on the spine due to contraction of these muscles may be considerably higher when kneeling. Another factor accounting for the difference in activity of the erectores spinae muscles in the two postures studied is that these muscles have been shown to become more quiescent when the spine is profoundly flexed (Floyd and Silver, 1955; Basmajian and De Luca, 1985; Gracovetsky and Farfan, 1986). In the stooped position, the lumbar spine is supported primarily by the paraspinal ligaments (Floyd and Silver, 1955; Gracovetsky and Farfan, 1986). Unfortunately, the strain imposed on these ligaments during lifting in the stooped posture is difficult to ascertain; however, we believe that the vertebral support function of the ligaments plays less of a role when lifting. The line of action in this task is in the re-extension direction; therefore, the erectores spinae would still be expected to exhibit considerable force.

The asymmetric nature of the lifting task studied appears to be manifest primarily in the activity of the latissimus dorsi and rectus abdominis muscles, and was only evident when lifting in the kneeling posture. Both the latissimus dorsi and rectus abdominis have relatively small cross-sectional areas; therefore, asymmetric lifting actions (especially twisting) may present a high risk of overexertion to these muscles. It is interesting to note that these same muscles have been found to be significantly affected by the velocity of lifting (Kim and Marras, 1987). Therefore, the role of the latissimus dorsi and rectus abdominis during lifting may be specialized in two ways: (1) to provide the force necessary for acceleration of the trunk, and (2) to provide disproportionate left and right side forces when necessary to perform asymmetric tasks.

The dynamic nature of the lifting tasks performed in this study requires that caution be exercised when interpreting the EMG results (Marras, 1987). As mentioned previously, the assumption was made that the back was in a static position for the purposes of the EMG analysis. While the motion of the back was not excessive during these lifting tasks, some movement of the trunk was unquestionably present. However, the finding that the erectores spinae exhibit increased activity (and thus increased muscle force) in the kneeling posture can be supported by examining the physiological data presented in this paper. It is well-known that oxygen consumption reflects use of adenosine triphosphate (ATP) by skeletal muscle. An increase in muscular contraction requires greater use of ATP, which, in turn, necessitates higher oxygen utilization for aerobic ATP resynthesis. The fact that oxygen uptake is increased in the kneeling posture indicates that, despite the reduction in the muscle mass used to perform the lift, overall ATP use is increased. This means that at least some of the muscles used for lifting in the kneeling posture must be contracting more vigorously. Based on the results of the EMG data, it would appear reasonable to speculate that a substantial portion of the increased ATP use in the kneeling posture as opposed to stooped is due to increased activity of the erectores spinae. The heightened demand upon these muscles is probably a result of their increased responsibility to counteract the moment about the L_5–S_1 joint due to lifting the box. Increased activity and static loading of other muscles, especially those of the shoulder and arms, may also help to account for the increased oxygen consumption demonstrated in the kneeling posture.

Biomechanical considerations

Both lifting postures examined in this study have considerable biomechanical disadvantages. For instance, the load on the intervertebral disks of the lumbar spine is known to be substantially increased in the stooped posture as opposed to upright standing (Nachemson, 1976). The shear forces acting on the intervertebral disks would also be expected to be considerable in this position. Another disadvantage of the stooped posture is that the back muscles are at their greatest length. Therefore, according to the relationship between length and strength of a muscle, less force can be exerted by these muscles. On the other hand, the stooped lifting posture would appear to have at least a couple of biomechanical advantages over kneeling. For instance, the shoulder moments experienced during stooped lifting would appear to be fairly low. This may be one factor accounting for the higher lifting capacity demonstrated in this posture. Another obvious advantage is the use of an increased muscle mass to perform the lift. The large muscles of the posterior leg and hip appeared to serve a useful role in lifting when stooped; in fact, this was often reported by the subjects as the area of greatest increase in muscle stiffness and soreness on days following the lifting tests. However, this role may be limited to the stabilizing influence these muscles have on the pelvis, and the restraining influence they provide to forward bending. Without exception, subjects placed their hands on knees between lifts in the stooped posture. This action is doubtless taken to reduce the strain on the low-back when lifting in this posture.

The mobility of an individual is greatly inhibited when working in the kneeling position as opposed to the stooped posture. In order to perform an asymmetric lift in the kneeling position, a twisting motion of the torso is virtually mandatory. The stability and balance of the body also seem to be decreased in the kneeling position. These factors may all play a role in influencing psychophysical lifting capacity. Another biomechanical factor worthy of consideration is that of ground reaction forces. It would be expected that the body's response to these forces would be substantially different in the two postures studied in the present investigation. For example, in the kneeling posture one does not have the same number of joints through which to dissipate these forces as in the stooped posture, and the muscles that must compensate for these forces are smaller. In fact, it may be that the back is one primary area where these forces must be absorbed when kneeling, whereas in the stooped posture the ankles and knees may help to reduce the burden placed on the back. In addition, the greater mobility afforded by working in the stooped position may allow increased opportunity to "fine tune" postural adjustments to reduce the stress on overworked muscles. Therefore, despite the fact that the trunk is more upright in the kneeling posture, many biomechanical factors may offset this advantage, making the kneeling pose equally (if not more) hazardous compared to the stooped position.

The difference in activity of the erectores spinae between these two postures has a significant bearing on the biomechanical modeling of restricted working postures. It is clear that biomechanical models that do not address the modification in muscular recruitment dictated by posture may provide unrealistic estimates of the forces experienced by the lumbar spine. Recently, however, a model has been developed that allows use of integrated EMG data to estimate muscular forces and, thus, compression and shear forces on the spine (Marras and Reilly, 1988; Reilly and Marras, in press). This model will be utilized by the Bureau of Mines to estimate the forces experienced by the lumbar spine in these two restricted postures.

Recommendations

Previous research has indicated that an acceptable weight of lift can be defined as one that can be safely lifted by 90 percent of an industrial population, as determined in a psychophysical study (Snook and Ciriello, 1974). Establishing an acceptable weight-lifting burden according to this criterion has been shown to significantly reduce the cost and incidence of low-back pain. Based on this criterion, the acceptable weight of lift for the stooped posture for this sample of underground miners is 25.7 kg (56.6 lb), while the acceptable weight of lift for the kneeling posture is 20.4 kg (45.0 lb). These values are based on a lifting frequency of 10 lifts/min for a 20-minute period, and apply to lifting compact loads. It should be stressed that only healthy, experienced miners (i.e, those screened to exclude prior serious back trauma or other health-related problems) were used in this investigation. Thus, these recommended weights may exceed the capabilities of less healthy workers, or those unaccustomed to lifting in the postures described in this paper.

The implications of the recommended weights described above are noteworthy due to the fact that the most commonly handled supply item in underground coal mines is the 50-lb rock dust bag. Based on the acceptable weight-lifting recommendations described above, 50 lb is an acceptable weight of lift for the stooped posture; however, it exceeds the recommended maximum for lifting in the kneeling posture. This outcome suggests that redesign of certain repetitively handled supplies should be given serious consideration. For instance, rock dust might be packaged in 40-.b bags instead of the current 50 lb in order to conform to the acceptable weight-lifting burden recommended for the kneeling posture. Redesign of other commonly handled supplies should also be examined. Such ergonomic redesign of supplies may have a significant impact on the problem of back injuries in low-coal mines.

CONCLUSIONS

Based on the results of this study, the following conclusions were drawn:

1. Psychophysical lifting capacity is reduced in the kneeling posture as compared with the stooped position, primarily as a result of the reduced muscular mass that can be recruited to perform the lift when kneeling.
2. Despite the fact that less weight was lifted in the kneeling posture, the metabolic cost of lifting on two knees is greater than when lifting in the stooped posture.
3. The erectores spinae are much more active when lifting in the kneeling posture than when stooped. Thus, the internal loading on the spine due to contraction of these muscles would be expected to increase. The latissimus dorsi and rectus abdominis muscles were used to control asymmetric motions in the kneeling posture.
4. Due to the reduced lifting capacity and increased metabolic and biomechanical stresses of lifting on two knees, serious consideration should be given to reducing the weight of materials that must be handled in the kneeling posture.

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REFERENCES

American College of Sports Medicine, 1980. Guidelines for Graded Exercise Testing and Exercise Prescription. Lea and Febiger, Philadelphia, 151 pp.

Asfour, S.S., Ayoub, M.M. and Genaidy, A.M., 1984. A psychophysical study of the effect of task variables on lifting and lowering tasks. J. Hum. Ergol., 13: 3–14.

Ayoub, M.M., Dryden, R., McDaniel, J. Knipfer, R. and Dixon, D., 1979. Predicting lifting capacity. Amer. Ind. Hyg. Assoc. J., 40 (12): 1075–1084.

Ayoub, M.M., Bethea, N.J., Bobo, M., Burford, C.L., Caddel, K., Intaranont, K., Morrissey, S. and Selan, J., 1981. Mining in Low Coal. Volume 1: Biomechanics and Work Physiology. Final Report U.S. Bureau of Mines contract No. H03087Ø22, 174 pp.

Ayoub, M.M., Selan, J.L., Karwowski, W. and Rao, H.P.R., 1983. Lifting capacity determination. In: Back Injuries, Proc. Bureau of Mines Technology Transfer Seminar. U.S. Bureau of Mines Information Circular 8948, pp. 54–63.

Basmajian, J.V. and De Luca, C.J., 1985. Muscles Alive, Their Functions Revealed by Electromyography. Williams and Wilkins, Baltimore, 561 pp.

Bobick, T.G., 1987. Analyses of materials-handling systems in underground low-coal mines. In: Proc. Bureau of Mines Technology Transfer Seminar. Bureau of Mines Information Circular 9145, pp. 13–20.

Borgen, F.H. and Seling, M.J., 1978. Uses of discriminant analysis following MANOVA: Multivariate statistics for multivariate purposes. J. Appl. Psychol., 63(6): 689–697.

Cailliet, R., 1981. Low back pain syndrome. F.A. Davis Company, Philadelphia, 230 pp.

Floyd, W.F. and Silver, P.H.S., 1955. The function of the erectores spinae muscles in certain movements and postures in man. J. Physiol., 129: 184–203.

Gallagher, S., 1987. Back strength and lifting capacity of underground miners. In: Proc. Bureau of Mines Technology Transfer Seminar. Bureau of Mines Information Circular 9145, pp. 21–32.

Games, P.A., Gray, G.S., Herron, W.L. and Pitz, G.F., 1980. ANOVR: Analysis of Variance on Repeated Measures. Behav. Res. Methods Instrum., 12: 467.

Garg, A. and Badger, D., 1986. Maximum acceptable weights and maximum voluntary isometric strengths for asymmetric lifting. Ergonomics, 29(7): 789–792.

Gracovetsky, S. and Farfan, H., 1986. The optimum spine. Spine, 11(6): 543–573.

Jorgensen, K., 1985. Permissible loads based on energy expenditure measurements. Ergonomics, 28(1): 365–369.

Kim, J.Y. and Marras, W.S., 1987. Quantitative trunk muscle electromyography during lifting at different speeds. Int. J. Ind. Ergon., 1(3): 219–229.

Krämer, J., 1981. Intervertebral Disk Diseases. Yearbook Medical Publishers, Chicago, 221 pp.

Liu, Y.K., Goel, V.K., Dejong, A., Njus, G., Nishiyama, K. and Buckwalter, J., 1985. Torsional fatigue of the lumbar intervertebral joints. Spine, 10 (10): 894–900.

MacDonald, E.B., Porter, R., Hibbert, C. and Hart, J., 1984. The relationship between spinal canal diameter and back pain in coal miners. J. Occup. Med., 26(1): 23–28.

Macnab, I., 1983. Backache. Williams and Wilkins, Baltimore, 235 pp.

Marras, W.S., 1987. Preparation, recording and analysis of the EMG signal. In: S.S. Asfour (Ed.), Trends in Ergonomics/Human Factors IV, Part B. Elsevier, Amsterdam, pp. 701–707.

Marras, W.S. and Reilly, C.H., 1988. Networks of internal trunk-loading activities under controlled trunk-motion conditions. Spine, 13(6): 661–667.

Mital, A., 1984. Comprehensive maximum acceptable weight of lift database for regular 8-hour shifts. Ergonomics, 27(11): 1127–1138.

Mital, A. and Fard, H.F., 1986. Psychophysical and physiological responses to lifting symmetrical and asymmetrical loads symmetrically and asymmetrically. Ergonomics, 29(10): 1263–1272.

Nachemson, A.L., 1976. The lumbar spine: An orthopaedic challenge. Spine, 1(1): 59–71.

Reilly, C.H. and Marras, W.S., in press. SIMULIFT: A Simulation Model of Human Trunk Motion. Spine.

Snook, S.H., 1985a. Psychophysical considerations in permissible loads. Ergonomics, 28(1): 327–330.

Snook, S.H., 1985b. Personal Communication.

Snook, S.H. and Ciriello, V.M., 1974. Maximum weights and work loads acceptable to female workers. J. Occup. Med. 16(8): 527–534.

Snook, S.H. and Irvine, C.H., 1967. Maximum acceptable weight of lift. Amer. Ind. Hyg. Assoc. J., 28(4): 322–329.

Snook, S.H., Irvine, C.H. and Bass, S.F., 1970. Maximum weights and workloads acceptable to male industrial workers. Amer. Ind. Hyg. Assoc. J., 31(5): 579–586.

Stegemann, J., 1981. Exercise Physiology. Yearbook Medical Publishers, Chicago, 345 pp.

U.S. Department of Health and Human Services, 1981. Work practices guide for manual lifting. Publication No. 81-122. National Institute for Occupational Safety and Health, Cincinnati, OH, 183 pp.