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An electromyographic analysis of an ergonomic intervention with the jackleg drill

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The jackleg drill is involved in more accidents than any other hand tool used in the underground metal/non-metal mining industries. A significant portion of these accidents are exertion injuries to the trunk. The experiments described in this paper were developed as a result of previous task and biomechanical analyses evaluating the operation of the jackleg drill. A simulated mine was developed where subjects were asked to perform transporting, positioning and removal tasks with and without an additional handle mounted on top of the drill casing. In addition, the positioning, collaring and removal tasks were conducted at three hole heights representative of those found underground. EMG results, along with predicted compression and shear via biomechanical modelling, indicate that the additional handle would need to be presented in conjunction with training in order to be an effective ergonomic aid.

Keywords: EMG analysis, miners, task analysis, drilling, working conditions, biomechanical modelling, handles

Introduction

Epidemiological analyses of the underground metal/non-metal mining industry have revealed that the jackleg drill is involved in more accidents than any other hand tool used in the industry. Over the six-year period from 1978 to 1983, the jackleg drill was associated with over 44% of all hand tool accidents in metal and non-metal mining (Marras *et al,* 1988). Further examination of the injury component sequences, with regard to the type of injury, the part of the body injured and the nature of the injury, has revealed that sequences involving both exertion and struck-by components were common during the use of this tool. While both sequences account for large numbers of injuries, it is suggested that many of the struck-by accidents could be controlled through better illumination of the workplace. However, there is no 'quick fix' solution to the exertion injuries. Therefore, this paper will concentrate on the etiology of the exertion injuries.

Observations of tool use and discussions with the workers revealed that the jackleg drill was very heavy, awkward, and required substantial strength to manipulate and operate. The use of the drill was observed during a routine drilling task. It was found that the task could be decomposed into 10 elements (see Fig. 1). When an ergonomics analysis was performed, several of these elements were identified as areas of biomechanical concern (Marras and Lavender, 1988).

For several of the task elements, it was hypothesised that the addition of a handle on the drill would ameliorate the biomechanical stresses when the operator was working at different hole-height levels. The task and ergonomics analyses also suggested that the benefits of a handle would depend on the task element. The positioning, collaring and removal elements were identified as elements where the addition of a handle would possibly reduce the likelihood of an exertion-type injury.

The analyses also revealed that the carrying element of tool use might also be involved in injury risk. The typical carrying task involved picking up the drill, transporting the drill stepping over obstacles, turning, and putting down the drill. The hypotheses suggest that the addition of a handle on the tool would also reduce the risk of injury in the carrying task.

Since the objective of this experiment was to assess the risk of exertion injuries to the back, the internal forces within the trunk were considered as the dependent measures. Previous research has demonstrated that the main forces that load the back during work result from the internal muscle forces (Marras *et al,* 1984). The muscles, due to the arrangement of the musculoskeletal system, are forced to work at a mechanical disadvantage. Thus, these internal muscle forces must be substantially greater than the external applied forces. In this study, the degree of trunk muscle activation was monitored via electromyography, using the peak and mean EMG levels.

Muscle selection was accomplished via the transverse plane analysis technique suggested by Schultz and Andersson (1981). This technique assumes that if an imaginary transverse plane were passed through the trunk, the internal structures which support and load the spine would be identifiable (along the plane). Using this technique, the left and right pairs of the erector spinae, latissimus dorsi and rectus abdominus muscles were identified as the muscles responsible for most of the trunk's internal forces. Through proper conditioning of the EMG signal, the force present

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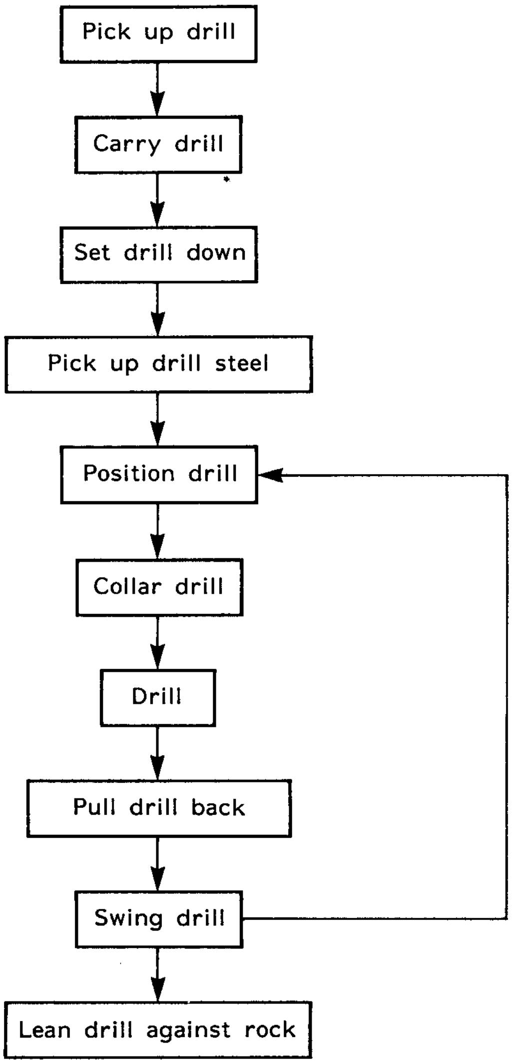

Fig. 1 Elements of drilling task with the jackleg drill

within the muscle is obtainable. This information can also be used as input to spine-loading models.

Two experiments were designed to investigate the trunk muscle loading while using the jackleg drill. The tasks represented in these experiments are those in which severe internal forces could be expected, and where an additional handle was expected to reduce the severity of the muscle and spinal loadings.

Experiment 1

Methods

The first experiment was designed to evaluate three tasks performed while operating the jackleg drill. These tasks, the orientation of the drill, collaring or starting a new hole with the drill, and the removal of the drill when the hole is completed, had been identified as strenuous to the lower back. All tasks were performed with and without an additional handle mounted on the drill casing. It was hypothesised that the ameliorating effects of an additional handle would probably interact with the height at which each task was performed. Therefore, the experiment investigated the biomechanical response at three levels of hole height.

Subjects

This study used eight male volunteer subjects between the ages of 23 and 39. The mean height and weight were 187·34 cm (s = 6·30 cm) and 88·25 kg (s = 11·17 kg). None of the subjects reported any prior incidence of low-back pain.

All subjects were initially novices with respect to jackleg drill operation. Subjects received training in handling and operating techniques typically used by miners. Each subject attended between one and three training sessions prior to testing, depending on their ability to perform the task effectively.

Experimental design

Due to time constraints involved with mounting and removing the handle, the handle variable served as a blocking factor. The ordering of the two handle conditions was counterbalanced with four subjects participating in the handle block first, and four subjects participating in the no-handle block first. Within each handle condition, the order of each task was randomised; within each task, the order of the hole height conditions was randomised. The experiment was a repeated-measures design where each subject participated in each cell of the experimental design. Within each cell, two trials were conducted. Data from the two trials were averaged before undergoing statistical analysis.

Apparatus

A simulated underground mine was constructed to mimic the conditions typical of the underground work environment. The key features of this laboratory simulation are shown in Fig. 2. The work area was 3·7 m long and 1·5 m wide. The roof was 2·7 m above the 10 cm thick loose gravel floor. At the front of the work area was the simulated 'rock face' constructed from wood. The rock face was 8·9 cm thick and as wide and as high as the workspace just described. Two holes were drilled at each of the three specified heights in the rock face. One set of three holes was filled with pipe caps to simulate the positioning and collaring tasks. These hole heights were 53, 118 and 205 cm. The other set of three holes was drilled completely through the face to test the drill removal task. These hole heights were at 53, 118 and 237 cm. The only lighting in the work area was from the caplamp worn by the subject. All subjects were issued hearing protection and were given gloves to wear while performing the experimental tasks.

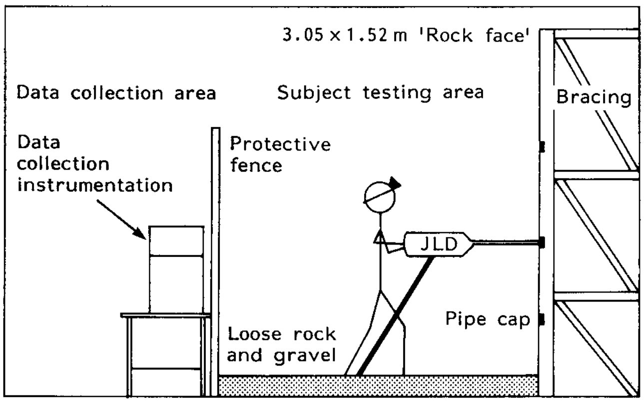

Fig. 2 Simulated mine

The jackleg drill used in the experiment was manufactured by Ingersol-Rand and weighed 52·2 kg. The tool was powered by means of an air compressor parked outside the room. A 5 cm diameter air line connected the drill with the compressor. There were two controls on the drill that the subject was required to operate (see Fig. 3). The first was the leg extension control. This control was made to be gripped by the operator's right hand and was mounted on the rear handle of the drill casing. The second control was the throttle control which was operated with the left hand. Mounted on the air leg of the drill was a handle, generally referred to as the 'D' handle. The 'D' handle is typically used when carrying the drill short distances. An additional handle was fabricated from hickory and aluminium that could be mounted and removed within a short period of time. Fig. 3 shows this handle and its orientation with respect to the drill casing and the operator. The anchor point of the air leg on the floor was controlled and constant for all subjects. The leg fork was hooked over a steel bar which served to prevent the leg from sliding when air pressure was applied.

Two lengths of drill steel were used. The 70-cm steel was used when testing the low and medium holes, while the 132-cm steel was used when testing the highest holes.

Procedure

Subjects were brought into the laboratory and prepared for EMG recording. The six muscles listed above were isolated and the skin prepared for electrode placement. At each electrode site, the skin was lightly abraded and conductive gel was applied. Two bipolar surface electrodes were placed on each muscle along its line of action 3 cm apart. Adequacy of skin preparation was checked by measuring the conductivity between the two electrodes. Values were checked for consistency in each pair between the left and right muscles. Electrode placement was verified using functional testing of each muscle sampled. Fig. 4 shows the electrodes connected to small preamplifiers placed on a belt worn by the subject. Each preamplifier was connected to an amplifier, after which the signal was rectified and integrated. The integrated signal was fed into an analogue-to-digital converter and then sampled by the computer at a rate of 50 samples (for each channel) per second. Following completion of the exertion, the data were transferred from the computer's memory to the hard disk in the computer for storage. As shown in Fig. 5, the signals were analysed for the peak and mean values during the exertion period.

Each subject's data collection session began with tests of maximal static exertions in postures similar to those required by the tasks. The peak values collected here were used in normalising the EMG data. For each subject the following normalisation procedure was used for each muscle:

$$\text{Normalised EMG} = \frac{\text{Observed EMG (i)} - \text{Resting EMG (i)}}{\text{Maximum EMG (i)} - \text{Resting EMG (i)}}$$

where: i refers to muscles 1 to 6.

Following tests for maximal exertions, tests using the three experimental tasks were conducted. Whether the handle was present or not was determined by the counterbalancing procedure. The tasks will not necessarily be described in the order presented since their order was randomised as described above.

The positioning task required the subject to orient and place the drill steel in one of the three selected pipe caps mounted in the 'rock' face. The order of the caps was selected using a random number table. The task began with the drill in what will be called the 'leg vertical' position. This is when the leg of the drill is vertical, not extended, and the drill is oriented horizontally. While orienting the drill, the subject was instructed to use the leg extension control where appropriate. If the subject was unable to place the steel either on the first attempt or after one corrective action, the trial was discontinued. Upon placement of the steel in the pipe cap, the subjects were instructed to turn the throttle on low to simulate the collaring task. The collaring task was performed for 3 s, after which the subject returned the drill to the leg vertical position. EMG data collection was initiated 1 s prior

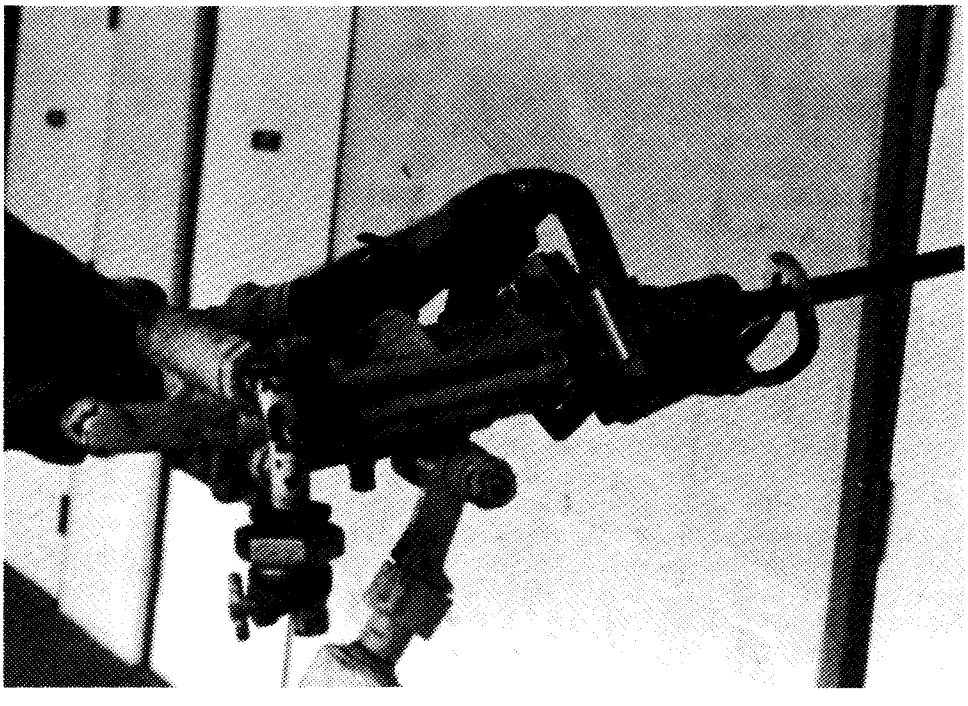

Fig. 3 Experimental handle mounted on top of the jackleg drill

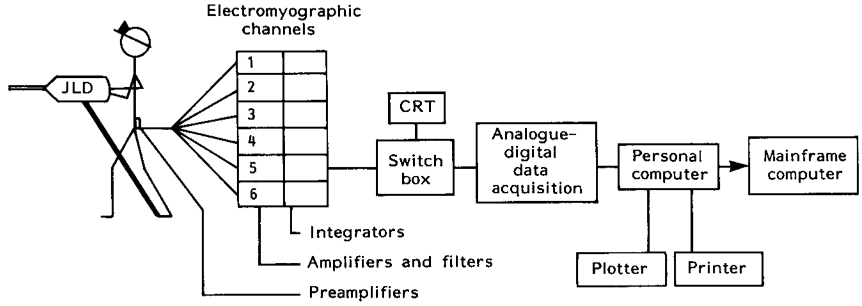

Fig. 4 Schematic diagram of the EMG data collection system

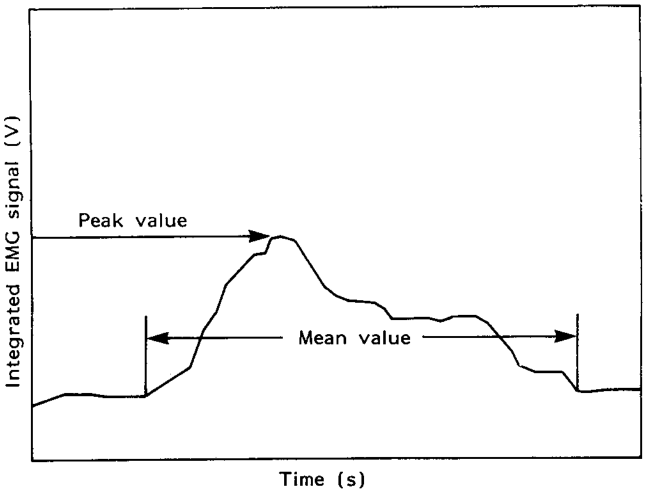

Fig. 5 Components of trunk muscle EMG activity used in the analysis

to the start signal given to the subject. The data were collected continuously until the collaring task was completed. When the subject turned on the drill throttle, the experimenter pressed a switch to mark in the EMG data where the orienting task ended and the collaring began. Each trial was repeated twice before proceeding to the next cell of the experimental design. In between each trial, the subject was given a 2-min rest period.

The drill removal task was set up with the drill steel inserted in one of the three holes (53 cm, 118 cm and 237 cm) in the rock face up to the steel retainer on the drill casing. The subject was instructed to remove the drill from the face and return it to the leg vertical position. EMG data were collected from 1 s prior to the exertion until the exertion was completed (approximately 3–5 s). Again, two trials were conducted at each hole height. Following the completion of the three tasks, the subject was given a 15-min break while the experimental handle was either removed from or mounted on the drill casing. Then the above procedure was repeated for the second block of trials.

Results

Positioning task

The multivariate and univariate statistical summaries for the jackleg drill (JLD) positioning tasks are presented in Table 1. This table indicates a statistically significant multivariate effect for both the mean and peak trunk muscle responses to handle condition, hole height condition, and between subjects. Univariate analysis of variance (ANOVA) procedures were used as follow-up procedures for the effects that were found to be significant according to the multivariate analysis of variance (MANOVA) tests. These ANOVA tests indicated that the right rectus abdominal muscle was responsible for the handle effect significance. *Post hoc* tests indicated that this muscle was significantly more active when the handle was attached to the drill

Table 1: Task–Positioning

Means		**Peaks**	
MANOVA effects		*MANOVA effects*	
Subject	P < 0·0001	Subject	P < 0·0001
Handle	P < 0·03	Handle	P < 0·05
Hole height	P < 0·002	Hole height	P < 0·05
Handle * hole height	NS	Handle * hole height	NS
Follow-up ANOVAs:		*Follow-up ANOVAs:*	
Muscles showing significant handle effects:		Muscles showing significant handle effects:	
RABR	P < 0·0015 (Handle > No handle)	RABR	P < 0·007 (Handle > No handle)
Muscles showing significant hole height effects:		Muscles showing significant hole height effects:	
ERSR	P < 0·0001 (Low = Med) > High	LATR	P < 0·0015 (Low = Med) > High
ERSL	P < 0·0035 (Low = Med) > High		

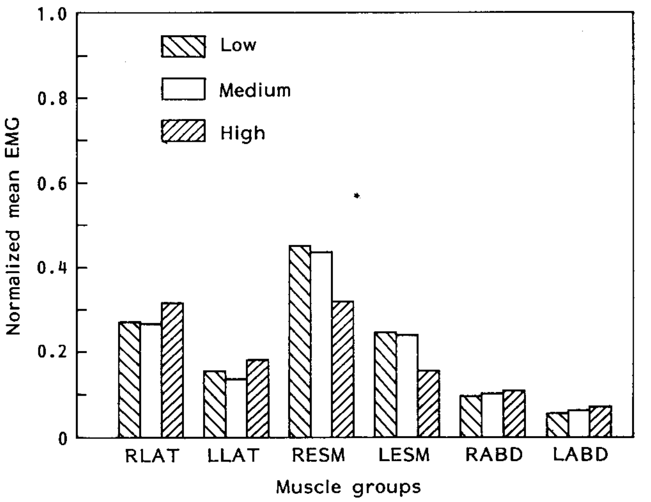

Fig. 6 Mean muscle response during the positioning task as a function of hole height

compared with the no-handle condition. This was the only muscle that behaved significantly differently to the handle condition.

More specifically, Table 1 and Fig. 6 show the mean muscle responses for both the right and left erector spinae were sensitive to the hole-height condition. *Post hoc* tests have indicated that for both the right and left erector spinae muscles the activity is significantly reduced under the high-hole conditions.

Significant handle and hole-height effects were also in MANOVA using the peak muscle activities. Peak muscle responses to handle conditions during positioning are shown in Fig. 7. As with the mean muscle responses, ANOVAs using peak muscle response only indicated the right rectus abdominal muscle was sensitive to the handle condition. The trend in the peak muscle response paralleled the mean response indicating that activity increased when the handle

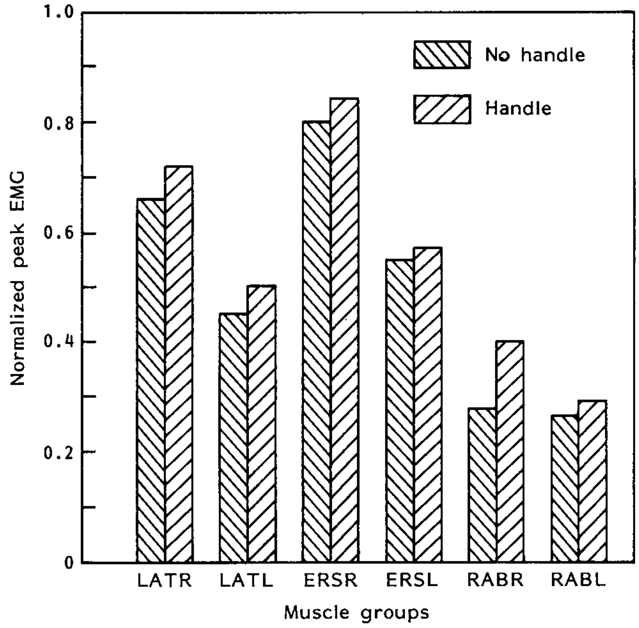

Fig. 7 Peak muscle response during the positioning task as a function of handle condition

was present on the drill. Table 1 also shows the peak muscle responses to hole-height conditions during positioning differed only for the right latissimus dorsi muscle. This muscle displayed increased peak muscle activity while positioning the drill at the low and high holes compared with the medium-height hole. This trend was prevalent, although non-significant, in three other muscles.

Collaring

The statistical summary of the mean and peak trunk muscle activities for the JLD collaring task is shown in Table 2. This table shows a significant subject and hole-height effect for the mean and peak trunk muscle activities.

Table 2: Task—Collaring

Means		**Peaks**	
MANOVA effects:		*MANOVA effects:*	
Subject	P < 0·0001	Subject	P < 0·0001
Hole height	P < 0·0001	Hole height	P < 0·0001
Follow-up ANOVAs:		*Follow-up ANOVAs:*	
Muscles showing significant hole height effects:		Muscles showing significant hole height effects:	
LATR	P < 0·0001 High > Med > Low	LATR	P < 0·0001 High > (Med = Low)
LATL	P < 0·0001 High > (Med = Low)	LATL	P < 0·01 High > (Med = Low)
ERSR	P < 0·0001 Low > (Med = High)	ERSR	P < 0·05 NS Trend
RABR'	P < 0·0001 (High = Med) > Low	RABR	P < 0·0003
RABL	P < 0·004 (High = Med) > Low		

The nature of the mean trunk muscle responses is shown in Fig. 8 for the various hole-height conditions. ANOVA analyses of these responses indicate that the right and left latissimus dorsi muscles, the right erector spinae muscle, and the right and left abdominal muscles all responded differently to the various hole-height conditions. The figure and *post hoc* analyses indicate that, for the latissimus muscles, the activity increases as the hole height increases. However, in the case of the left muscle, there was no statistically significant difference in response between the low and medium height holes. The erector spinae muscle exhibited significantly greater activity in the low hole position compared with the medium or high hole conditions. Finally, the rectus abdominus muscles exhibited significantly greater activity at the medium and high hole conditions compared with the low hole condition.

The peak muscle activities as functions of hole height for the collaring task are shown in Fig. 9. The ANOVA and *post hoc* tests indicate that the MANOVA significance was due to the activity of the right and left latissimus dorsi muscles, the right and left erector spinae muscles, and the right rectus abdominus muscle. The trend for the latissimus dorsi muscles indicated that the muscle activity at the high hole was significantly greater than at the medium or low holes. The right erector spinae muscle showed significantly greater activity while collaring in the low hole. Also, the right abdominal muscle displayed greater activity at the medium and high holes compared with the low hole. However, the general trend indicated that the muscle activity increased as hole height increased.

Drill removal task

A statistical summary for the mean and peak muscle activity during the JLD removal task is shown in Table 3. This summary table indicates that significant multivariate effects due to the subject, handle and hole height are present only when the mean trunk muscle activity is considered. The ANOVA analysis showed that no single muscle response was

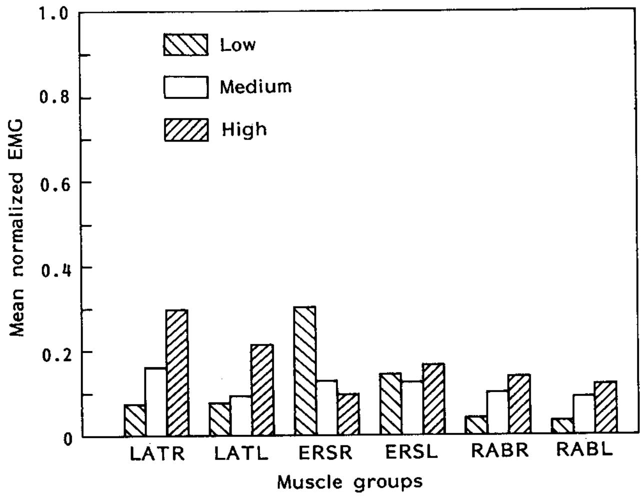

Fig. 8 Mean muscle response during the collaring task as a function of hole height

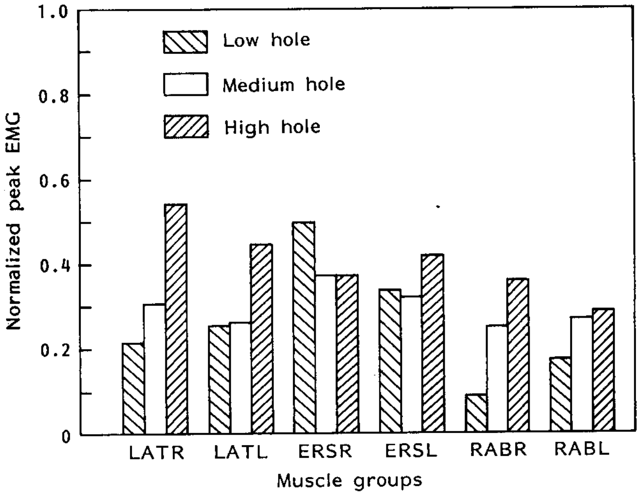

Fig. 9 Peak muscle response during the collaring task as a function of hole height

Table 3: Task—Removal

Means		Peaks	
MANOVA effects:		*MANOVA effects:*	
Subject	P < 0·0001	Subject	P < 0·0001
Handle	P < 0·03	Handle	NS
Hole height	0·0006	Hole height	NS
Handle * hole height	NS	Handle * hole height	NS
Follow-up ANOVAs:			
Muscles showing significant handle effects:			
None with	P < 0·05		
Muscles showing significant hole height effects:			
LATR	P < 0·0005 High > (Low = Med)		
ERSL	P < 0·0002 (Low = Med) > High		

responsible for the significant multivariate reaction to handle effects. However, the presence of a significant multivariate effect indicates that the biomechanical system did respond differently as a function of the handle's presence or absence. The effects of hole height on mean muscle responses during drill removal are shown in Fig. 10. The ANOVA summaries indicated that the right latissimus dorsi and left erector spinae muscles both exhibited significantly different responses to the hole-height conditions. The latissimus dorsi muscle showed the greatest response to the high hole condition when compared with the low and medium hole conditions. The erector spinae muscle did not exhibit any significantly different responses between the low and medium height holes; however, the responses to both of these conditions were significantly greater than for the high-hole condition.

Table 3 also indicates that there are no significant multivariate or univariate effects to the handle or hole height conditions or to their interaction when the peak muscle activities are considered.

Compression analysis through biomechanical modelling

The continuous muscle responses were also used to predict peak spine compression and shear forces. The SIMULIFT biomechanical model developed by Reilly and Marras (1989) was used to predict these impulse forces on the spine. These analyses indicate that the positioning and removal tasks involve a particularly significant risk of spine overload. Figs. 11 and 12 show the compressive forces during the JLD positioning and removal tasks. The scale on the right-hand side of the compression plots indicates the risk of vertebral endplate microfracture based upon values presented in the *Work Practices Guide for Manual Lifting* (NIOSH, 1981). No such comparisons are available for the shear forces at this time.

Table 4 summarises the statistically significant differences in compression and shear due to the experimental treatments during the three JLD tasks. This table, in conjunction with Fig. 11, indicates that for the positioning task, spinal compression increases as hole height decreases. During drill positioning, the risk of vertebral endplate microfracture exists for all hole-height conditions. The risk is greatest (about 4%) for the low hole condition when the handle is used. Interestingly, in the high hole condition, spine compression is less when the handle is used. The shear estimates for the various positioning components were low and, as Table 4 shows, not significantly different between conditions. It must be pointed out that no shear risk values are available; therefore, it is difficult to make an absolute judgement about the risk due to shear forces for the various JLD tasks.

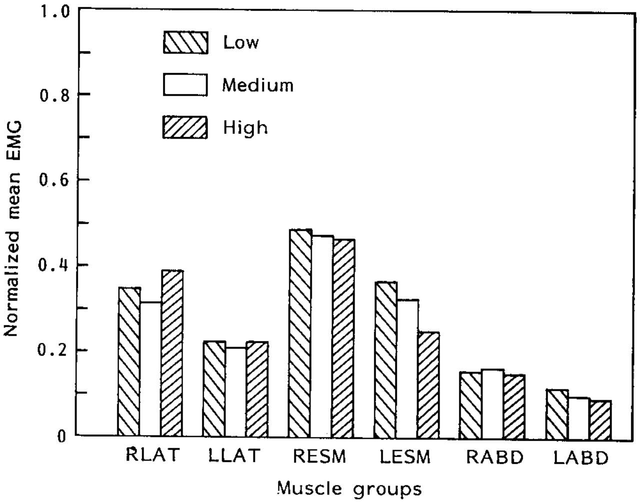

Fig. 10 Mean muscle response during the removal task as a function of hole height

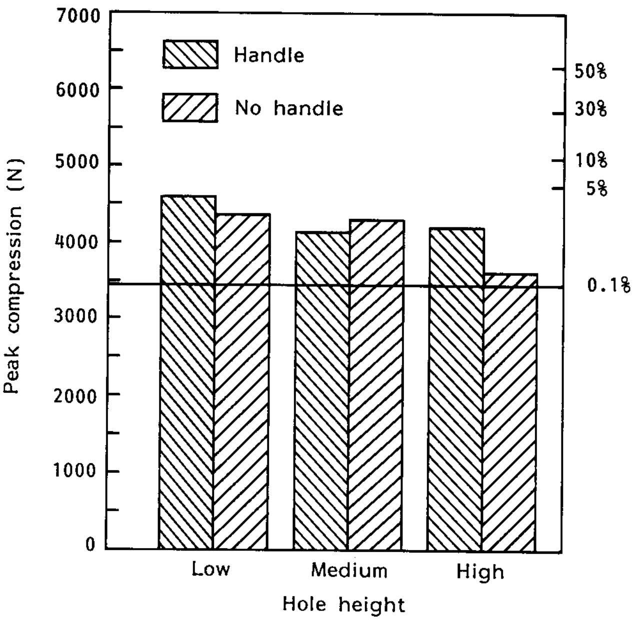

Fig. 11 Predicted spinal compression at the L5/S1 level using the simulift model (Reilly and Marras, 1989) during the positioning task

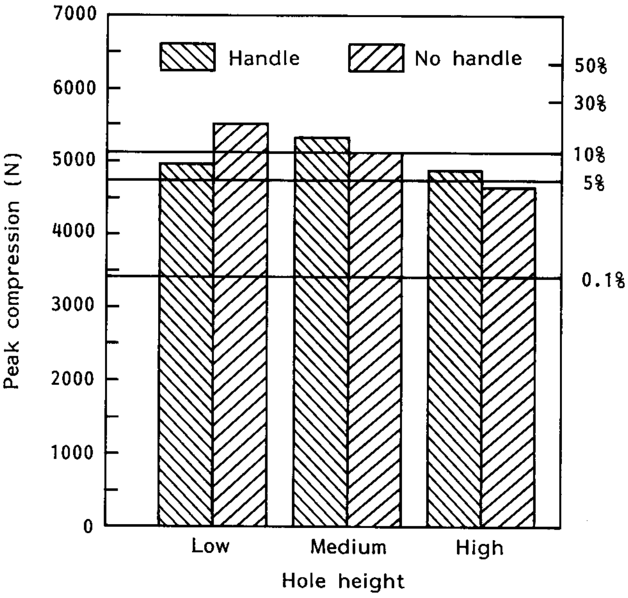

Fig. 12 Predicted spinal compression at the L5/S1 level using the simulift model (Reilly and Marras, 1989) during the removal task

Fig. 12 shows that during the drill removal task, the compression risk varied from 4% to 20% as a function of the experimental conditions. Table 4 also shows a significant

Table 4: Compression and shear results

Positioning:	Compression	Hole height	P = 0·0582 Low > High
	Shear		NS
Collaring:	Compression		NS
	Shear		NS
Removal:	Compression	Hole height	P < 0·02 (Low = Med) > High
		Handle * Hole height	P < 0·05 (See Plot)
	Shear		NS

hole-height difference and handle–hole-height interaction. The low- and medium-height holes resulted in greater compression values than did the high hole. Fig. 13 shows the nature of the interaction. This figure indicates that spine compression was substantially reduced (600 N) at the low hole condition by providing the operator with a handle. However, for the medium and high holes the inclusion of a handle increased compression by about 200 N. Once again, the spine shear during drill removal was low and did not statistically differ among experimental conditions.

Figures showing the compression and shear predictions for the various components of the collaring task are not shown here. Results indicate that the compression and shear values for the collaring task were both low and were not significantly different between experimental conditions.

Experiment 2

Methods

The second experiment investigated the internal forces generated while carrying the jackleg drill as a function of an additional handle mounted on the drill casing and the nature of the carrying task. It was hypothesised that the presence of a handle on top of the drill casing would aid in redistributing the load to be more sagittally symmetric. Non-sagittally symmetric (asymmetric) loading increases the shear components during spinal loading. High shear components have been suggested as a likely causal agent in the development of low back disorders (Lavender *et al,* 1989). The following experiment investigated the change in internal forces due to the types of carrying tasks performed.

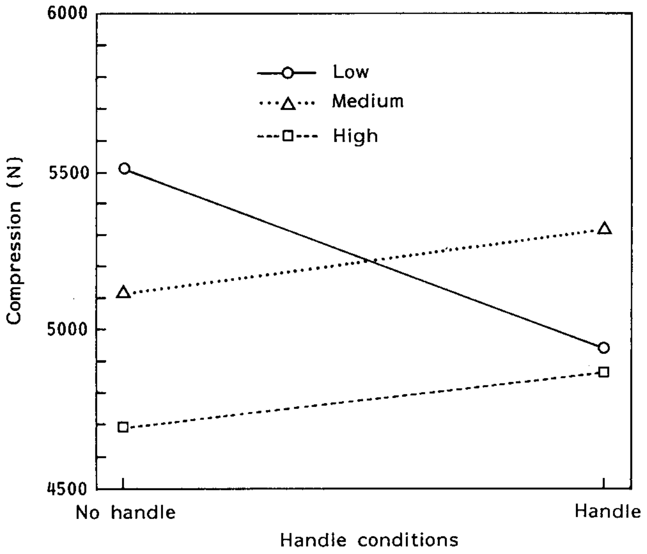

Fig. 13 Hole height and handle condition interaction for the predicted compression during the removal task

Subjects

The eight subjects who participated in the previous experiments were also recruited for the present study. Subjects were compensated with an Ohio State Biodynamics Laboratory T-shirt for their efforts.

Experimental measures

The experiment investigated the internal forces when the handle was present or not present. The internal forces measured were from the left and right latissimus dorsi, the left and right erector spinae, and the left and right rectus abdominus. Again, the peak and mean EMG signal during the selected periods were used in the data analysis.

Apparatus

The experiment was carried out in the simulated mine environment described above, and with the same jackleg drill. An obstacle 20-cm high was placed in the subjects' path to simulate the cluttered floor conditions observed underground. A red line painted on the gravel served as a marker for the subject to turn around.

The additional handle used in this experiment is the same handle described above and pictured in Fig. 3. Likewise, the data collection system described in the above experiment was also used in this study.

Procedure

Subjects were prepared for EMG data collection as previously described. The experimental task required the subjects to pick up the drill from its position leaning against the simulated rock face, walk the length of the mine simulator (stepping over the obstacle), turn 180°, walk the length of the simulator (again stepping over the obstacle) and replace the drill in its initial position. Subjects were instructed, in the handle condition, to pick up and carry the drill with the experimental handle in the left hand, and the 'D' handle in the right hand. In the absence of the experimental handle, subjects were instructed to cradle the drill body in their left arm and grasp the 'D' handle with their right hand. Subjects were instructed to pause 1 s after picking up the drill and following the 180° turn.

EMG data were collected from 1 s before the task was initiated until the drill was replaced. The experimenter used a marker switch to indicate where each event in the experimental procedure occurred. Two trials were collected for each of the two handle conditions for each subject.

Results

The task and handle effects were tested for statistical significance and these results are shown in Table 5. This table indicates a significant multivariate effect of subjects, handle and task on the mean muscle activity. The mean muscle reactions to the various tasks associated with JLD carrying are shown in Fig. 14. The univariate ANOVAs indicate that there were significant differences in activities of the left latissimus dorsi, right and left erector spinae and left abdominal muscles as a function of the carrying tasks. These tests indicated that different muscles can be considered responsible for trunk control during the various phases of the task. For example, the left latissimus dorsi muscle showed significantly greater activity in the replacing task compared with the other tasks. The right erector spinae muscle exhibited increased activity for the transporting and turning tasks compared with the other tasks. The left erector spinae activity was least for the replacement task compared with the other tasks. And finally, the follow-up analyses show the left abdominal muscle to have greater activity during transporting compared with lifting the drill.

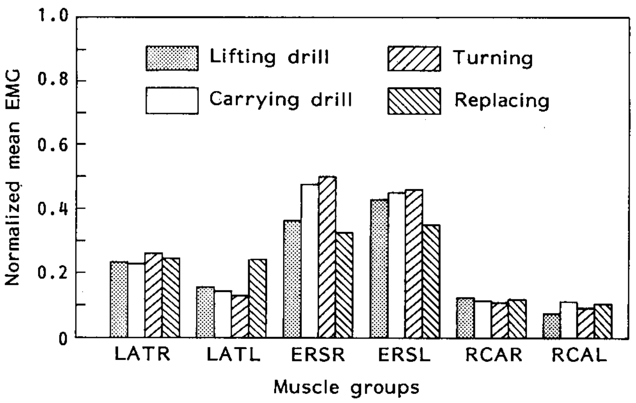

Fig. 14 Mean muscle response during the transporting task as a function of the subtasks evaluated

With respect to the handle conditions, only the activity of the right latissimus dorsi muscle was affected. The *post hoc* tests indicated that the handle conditions required substantially more activity than the no-handle condition.

The peak muscle activities were also evaluated for their sensitivity to the experimental conditions. Table 5 indicates that significant multivariate handle, task and subject effects are present, but their interactions are not significant. The univariate ANOVAs indicated that the left latissimus dorsi muscle was most responsible for the multivariate significance. This muscle displayed much greater activity for the replacing task compared with the other three tasks. Only the right latissimus dorsi muscle showed a significantly different response to the handle condition. As shown in Fig. 15, this peak muscle activity was about 20% (of maximum capacity) greater during the handle-on condition. While all muscles showed relatively high peak activities during the carrying

Table 5: Jack leg drill carrying experiment

Means		**Peaks**	
MANOVA effects:		*MANOVA effects:*	
Subject	$P < 0\cdot0001$	Subject	$P < 0\cdot0001$
Handle	$P < 0\cdot0002$	Handle	$P < 0\cdot0001$
Task	$P < 0\cdot0001$	Task	$P < 0\cdot0001$
Handle * task	NS	Handle * task	NS
Follow-up ANOVAs:		*Follow-up ANOVAs:*	
Muscles showing significant handle effects:		Muscles showing significant handle effects:	
LATR	$P < 0\cdot0001$ (Handle > No handle)	LATR	$P < 0\cdot0001$ (Handle > No handle)
Muscles showing significant task effects:		Muscles showing significant task effects:	
LATL	$P < 0\cdot0001$ *Rep > (Lift = Walk = Turn)	LATL	$P < 0\cdot0001$ *Rep > (Lift = Walk = Turn)
ERSR	$P < 0\cdot0001$ (Turn = Walk) > (Lift = Rep)		
ERSL	$P < 0\cdot008$ (Turn = Walk = Lift) > Rep		
RABL	$P < 0\cdot02$ Walk > Lift		

*Rep = Replace drill

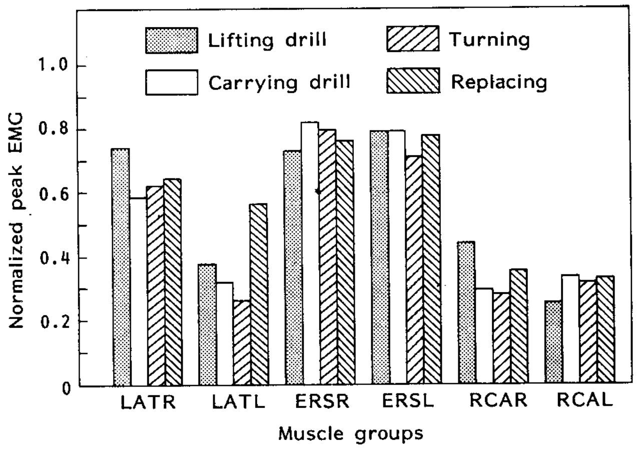

Fig. 15 Peak muscle response during the transporting task as a function of the subtasks evaluated

task, no other muscles displayed significant peak activity differences as a function of the experimental conditions.

The spine compression and shear forces were not computed for the JLD carrying experiment. The SIMULIFT model normally used to predict these forces is valid only for situations where trunk activity is static or the back is moving under constant velocity conditions. A review of the trunk activity in this experiment showed that these assumptions were not valid during the carrying tasks. Thus, neither spine compression nor shear forces could be analysed.

Discussion

These results have evaluated the risk of back loading due to the performance of the JLD tasks which were identified as potential problem activities via the task analysis and ergonomics assessment. The first experiment evaluated the positioning, collaring and removal tasks associated with using the JLD. The second experiment evaluated the lifting, transporting, turning and replacement tasks associated with JLD transport.

The JLD use will be discussed first. This evaluation has shown that the strain experienced by the trunk muscles during drill positioning is a function of both the handle and the height of the hole being drilled. The average and peak load on the right abdominal muscle increased by about 10% of maximum when the handle was used to position the drill. The other muscles did not display any significant change in activity. Hole height appeared to have a much greater influence on the activity level of the muscles. The mean activity of both erector spinae muscles significantly increased (about 20% of maximum) when subjects positioned the drill at the low and medium height holes compared with the high holes. This is particularly important since the erector spinae muscles are very large in their cross-sectional area, which means that a small increase in muscle activity results in a large increase in muscle load. The spine compression modelling confirmed these findings. This assessment indicated that the low hole condition produced significantly greater compression on the spine compared to the high hole condition. When the compression values were compared with the risk of vertebral end plate fracture, it was found that there is between a 1% and 4% risk of fracture. Even though these values are low, the cumulative effect of positioning the drill should be kept in mind. This task should be considered potentially hazardous. This analysis has also found that control methods, such as the addition of handles, do not offer any biomechanical advantage during positioning but actually increase the loading on the trunk.

The assessment of the collaring task showed that the load on the muscles was affected by the height of the hole. A trade-off in muscle loading was observed in this case, with increased activity occurring in the latissimus dorsi muscles and abdominal muscles while collaring the high holes, and increased activity occurring in the erector spinae muscles while collaring the low hole. The spine-force analysis showed that this may truly be a trade-off in that there is no statistically significant difference in the compression or shear spine forces as a function of the various experimental conditions. The task of collaring would not be considered risky in terms of spine loading. The levels of compression imposed upon the spine during the performance of this task are well within acceptable limits.

The drill removal task indicates that both the handle and hole-height factors have an effect on trunk muscle activities. In this case, we again see a trade-off in muscle load between muscle groups. The latissimus dorsi muscles exhibit greater activity at the high holes, whereas the erector spinae muscles follow the opposite trend. The true risk of this task can be appreciated by observing the spine compression predictions. This analysis shows a significant handle by hole-height interaction as well as a hole-height main effect with regards to spine compression. The low and medium height holes significantly increase spine compression. However, this increase can be mediated at the low hole by including a handle on the drill. The spine-compression analysis indicated that the risk associated with this task was between 4% and 20%, which is much greater than the risk associated with any other task. This risk can be reduced by an average of 12% at the low hole through the use of a handle. However, that is only true for the low hole. The risk associated with this task may be even greater considering that the task analyses revealed a tendency for the drill steel to stick in the hole. This event would create even greater forces on the back, particularly if a sudden unexpected jolt is imposed on the spine.

The carrying task components were also evaluated in this study. This evaluation indicated that both handle and the task conditions affected the load on the trunk muscles. Inclusion of a handle for use during the transporting task had the effect of increasing the activity of the right latissimus muscle by about 10%. All other muscles were unaffected by using the handle. When the tasks associated with carrying were considered, it was apparent that the erector spinae muscles were the most active muscle group in the trunk. The average muscle activity approached 50% of maximum for most tasks, and peak activities as high as 80% of maximum were observed for certain task components. This muscle group was significantly more active during the transporting of the drill and during the turning motion as compared with the lifting or replacing activities. The left latissimus dorsi muscle also showed an increase of about 10% during the replacement task. These patterns appear typical of a manual materials handling task. The erector spinae muscles appear to bear most of the load during the drill lifting and the muscle activity increases during the transporting and turning tasks. This is probably due to a static overload condition occurring in the back muscles. Since the muscles are fatiguing during this time, more muscle fibres must be recruited to maintain the desired force and posture. The latissimus dorsi muscles, on the other hand, respond to changes in activity such as lifting or lowering the drill. The fact that only one of these muscles changes its activity indicates that the tasks impose asymmetric forces on the spinal structures.

Even though spine-force predictions were not generated for the transporting activities task, the magnitude of the muscular activity of the spine-supporting structures can be used as a basis of comparison for spine compression. The spine compression would be expected to be quite high during the lifting and lowering tasks since the erector spinae peak activities are as high as 80% of maximum. Similar muscular activity of the erector spinae was observed during the stressful removal task. Thus, since this muscle group is one of the main loading muscles of the spine, the total compression during the carrying tasks is expected to be unacceptable.

This analysis has indicated that there are components of the JLD-use tasks that are hazardous. Particularly, the removal, carrying and, to a lesser extent, the positioning tasks have been identified as risky. Based upon the findings of this study, several solutions are indicated that may improve this situation.

First, reducing the weight of the tool would be expected to reduce the loading on the spine. This is especially true in the carrying tasks as this is an example of an extreme material handling condition. Even in the positioning and removal tasks, where much of the tool weight is resting on the leg, a reduction in tool weight should reduce the muscle forces necessary for tool manipulation.

Second, this study has shown that the risk of injury can be reduced by providing a handle for drill removal from low holes. However, under other circumstances, the spine loading actually increases when the handle is used. Thus, one possible solution is to provide a handle, and training for the operator when to use or not use the handle. The problem with this solution is that training effects generally do not last very long and the worker may actually be worse off with this tool redesign (Snook *et al*, 1978). Also, as seen in the analysis, even using the handle at the low hole, the spine compression values are unacceptable.

Finally, the recommended solution is to use the JLD while mounted on an articulated arm connected to a mining vehicle. Understandably, this is not a complete solution, as miners are often required to work from the top of muck piles and other locations inaccessible to mining vehicles. Therefore, alternative mounts could be developed whereby an articulated arm could be mounted to a substantial support post wedged between the roof and the floor. Such a system could be designed to break down into components that can be safely handled and transported by a single person. This would eliminate the need to manipulate the tool physically by using exertions that over-stress the trunk system.

In summary, this paper has shown, with regard to the tasks sampled, that no simple modification to the tool, short of reducing the overall weight, is likely to reduce the internal forces consistently. The additional handle proved only to be useful in reducing trunk muscle forces in very specific instances. This information, while generally a negative result, should be useful to those seeking solutions to the man-machine interfacing problem encountered with the JLD. In addition, this paper provided a quantitative analysis of the internal forces necessary to perform common tasks while using the JLD. Such data should prove useful in the future in evaluating other proposed modifications to this tool.

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References

Lavender, S.A., Mirka, G.A., Schoenmarklin, R.W., Sommerich, C.M., Sudhakar, L.R., and Marras, W.S. 1989, *Human Factors,* in press. The effects of preview and task symmetry on trunk muscle response to sudden loading.

Marras, W.S., Lavender, S.A., Bobick, T.G., Rockwell, T.H., and Lundquist, R.L. 1988, *J Safety Res,* **19**, 115–124. Risks of hand tool injury in US underground mining from 1978 to 1983. Part II: Metal–Non-metal mining.

Marras, W.S., and Lavender, S.A. 1988, An analysis of hand tool injuries in the underground mining industries. Final Report prepared for the Bureau of Mines, US Dept of the Interior, Contract J0348043.

Marras, W.S., King, A.I., and Joynt, R.L. 1984, *Spine,* **9**, 176–187. Measurements of loads on the lumbar spine under isometric and isokinetic conditions.

NIOSH. 1981, Work practices guide for manual lifting. DHHS (NIOSH) Technical Report No 81-22, US Dept of Health and Human Services, Cincinnati, OH, USA.

Reilly, C.H., and Marras, W.S. 1989, *Spine,* **14**, 5–11. SIMULIFT: A simulation model of human trunk motion.

Schultz, A., and Andersson, G. 1981, *Spine,* **6**, 76–82. Analysis of loads on the lumbar spine.

Snook, S.H., Campanelli, R.A., and Hart, J.W. 1978, *J Occup Med,* 478–481. A study of three preventive approaches to low back injury.