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The effects of method of use, tool design, and roof height on trunk muscle activities during underground scaling bar use

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Epidemiologic studies have shown that the scaling bar, a hand tool used in underground mining, is frequently associated with the risk of back injury. An experiment was performed to investigate the effects of method of tool use, mine roof height, and tool design upon the activity of six trunk muscles and the ability to exert force with the bar. Roof height and scaling bar design had the largest effects on levels of muscle activation. Striking force did not differ significantly between tool designs. A biomechanical model was used to evaluate the collective effects of the trunk musculature activities upon spine loading. It was found that a significant reduction in predicted spine compression and shear forces can be achieved through the use of a counterbalanced scaling bar. The implications of these results are discussed.

1. Introduction

In underground mining the scaling bar is a ubiquitous tool that is commonly used to remove loose rock fragments from the roofs of mines. In many instances this tool is used daily by workers in both coal and metal/non-metal mining. Over the years this tool has also been associated with a large number of injuries. Marras *et al.* (1988a, 1988b) reviewed six years of US mining injury data in an epidemiologic study that associated the risk of injury in underground mining with the use of various hand tools. In this study, they found that over 26% of hand tool-related lost time accidents in the coal industry during this time period were associated with the use of the scaling bar, whereas in the metal and non-metal mining industry over 40% of all hand tool-related lost time accidents were associated with the use of this tool. Relative to other hand tools used in underground mining, the scaling bar ranks highest as a cause of days lost from work in coal mining, and, second only to the jackleg drill, of days lost from work in metal/non-metal mining. In both of these types of mining it was also found that a substantial number of these scaling bar injuries involved over-exertion injuries to the back.

These studies also identified tool-use scenarios that are associated with increased risk of injury when using hand tools such as the scaling bar. The focus of the present study was to investigate empirically the mechanisms of injury associated with the use of this tool in underground mining environments.

The scaling bar typically consists of a piece of bar metal stock with a diameter between 2·5 and 4 cm. A sharp tip is either ground into one end, or a preformed tip is attached to the end of the bar. These bars, depending on the length and type of material used in the bar, are typically between 1·22 and 3·66 m in length and can have a mass greater than 4 kg. Commercially-available scaling bars, usually made of Fibreglass, are also becoming commonplace in the mining environment.

Marras and Lavender (1988) performed underground video observations of seven types of underground mining operations and performed task analyses of scaling bar use in these operations. These observations identified three possible factors that may affect spine loading and the risk of back over-exertion injuries through the use of the scaling bar.

The first factor was the method of scaling. The task analyses showed that there were three phases of scaling bar use. These phases consisted of orienting the bar, thrusting (and prying) the bar to a point on the roof, and recovery so that the process could begin again. The analyses also indicated that there were several variations in the method of tool use for accomplishing the roof scaling task. These variations are not necessarily in agreement with the methods suggested in training presentations used by the US Bureau of Mines. This latter method requires the miners to have their elbows pronated and above shoulder height. The purpose of this position is to allow the miner to be further from the scaling target and put the forearm in a position where falling debris can be deflected before striking the torso or head. This method, while recommended, was not commonly observed. The most frequent method of scaling bar use encountered underground had the miner working with a supinated grip and the forward upper arm not abducted while in the resting position. It was hypothesized that variations in method may impose different biomechanical loadings upon the spine during work.

The second factor that may affect spine loading was the physical properties of the scaling bar. The scaling bars used underground vary along the dimensions of length, weight, and diameter. The length is a critical measure since this affects how close the miner has to be to the loose roof material when scaling. The weight of the bar determines the external loading placed on the miner during the orienting, thrusting, and recovery phases of the task. The centre of mass of the bar creates an external moment about the spine against which the trunk musculature must act. It was hypothesized that decreasing the bar weight would decrease the moment and the required trunk muscle force necessary to counteract the bar moment during the task. However, reducing the weight of the bar may also decrease the inertial properties of the bar and may reduce the strike force between the bar and the rock. For this reason, it was believed that one may modify a lightweight scaling bar by adding a counterbalance so that the weight of the bar was the same as a standard bar, but the counterweight would have the effect of moving the centre of mass of the bar closer to the worker's spine, thus reducing the magnitude of the moment imposed about the spine.

Finally, the third factor expected to influence spine loading is the roof height of the mine. Underground mines vary greatly in roof height from approximately 0·76 m to greater than 3·65 m. The work postures related to roof height may be a contributing factor in the etiology of scaling exertion injuries. Low roof heights require miners to work in kneeling or stooped postures, imposing greater loads on the spine as the worker has limited opportunity to transfer loading from the back to the legs (Gallagher 1987, Gallagher *et al.* 1988).

The following experiment was designed to investigate these three factors with respect to the levels of trunk muscle activity required to perform a scaling task. The goal was to gain a basic understanding of how the body responds to these factors. Specifically, the following research addressed whether differences can be observed in levels of trunk muscle activity as a function of the method of scaling used, the type of bar used, and the height of the roof (and thereby the work posture used) when the task is performed.

2. Method

2.1. *Subjects*
Fourteen male subjects volunteered their services for the study. Only two subjects had any previous experience scaling in an underground environment. In this subject pool, the mean height was 177·2 cm (s=12·3 cm), and the mean weight was 79·12 kg (s=11·88 kg). All subjects were healthy, and none was experiencing back pain at the time of the experiment.

2.2. *Experimental design*
In this experiment the subjects were asked to perform a simulated roof scaling task under various experimental conditions. The work pace was controlled and the environmental conditions were as realistic as possible. The activities of key trunk muscles that are believed to be responsible for trunk loading were monitored during the performance of the task. In this manner an appreciation of the effects of task variables upon the risk of trunk injury could be gained.

The independent variables investigated in the present study included method of bar use (2 levels), bar type (3 levels), and roof height (2 levels). The two methods of scaling investigated consisted of that method suggested by the US Bureau of Mines (overhand) and the method most often observed in the field (underhand). The three bar types investigated consisted of a commercially-available Fibreglass bar (standard), a lightweight bar (light) and a counterbalanced bar (ctr-bal). The roof height conditions consisted of a 251 cm roof height that required the subject to perform the task while standing (high), and a 141 cm roof height that required the subject to perform the task while in a kneeling position (low). In both of these conditions the subject's trunk was in an upright static position while he performed the scaling task. This situation facilitated the assessment of the muscle activities via electromyography.

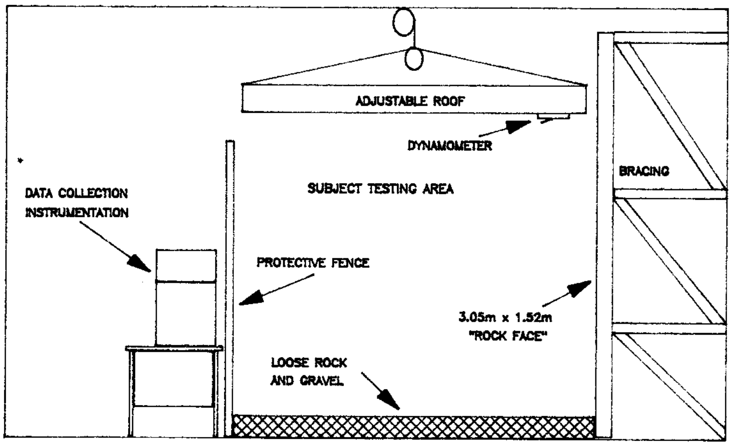
Thirteen dependent measures were recorded. Twelve of these measures consisted of the mean and peak electromyographic (EMG) activities recorded from the six key trunk muscles. These six muscles were observed in the following three muscle groups:

1. left (LATL) and right (LATR) latissimus dorsi muscles;
2. left (ERSL) and right (ERSR) erector spinae muscles;
3. left (RCAL) and right (RCAR) rectus abdominus muscles.

In addition, the relative strike forces exerted against the roof with the scaling bars were collected from a three-axis load cell.

The experiment was blocked on roof height while the sequence of bar type and method of testing was randomized. A repeated measures design was used with all subjects participating in all cells of the experiment.

2.3. *Apparatus*
The experiment was conducted in a simulated mine environment (see figure 1). The front of the mine had a 9 cm thick wooden wall serving as the working face. An adjustable ceiling was designed to simulate the varied roof conditions. In this experiment, the roof height was adjusted to either 141 cm or 251 cm. The floor was covered with approximately 8 cm of gravel so as to simulate the loose surface miners typically stand on. Bolted to the roof was a three-axis load cell mounted



Simulated Mine

Figure 1. Experimental mine layout.

in such a manner that it resembled mine roof surface. This load cell served as a target in the scaling task.

Three scaling bars were used. The first, referred to as the standard bar, is a commercially-available Fibreglass bar. The second, referred to as the light bar, was constructed from aluminium tubing in order to be as light as possible. This served as the minimum external loading condition while performing the scaling task. The third, referred to as the counterbalanced bar, while weighing the same as the standard bar, was designed to bring the centre of gravity of the bar as close to the operator as possible. All bars used steel tips that screwed into the ends. The relevant dimensions of the bars are presented in table 1 and shown in figure 2.

Subjects were provided with gloves, hard hats, and cap lamps to be worn while performing the task. The cap lamp was the only light available to the

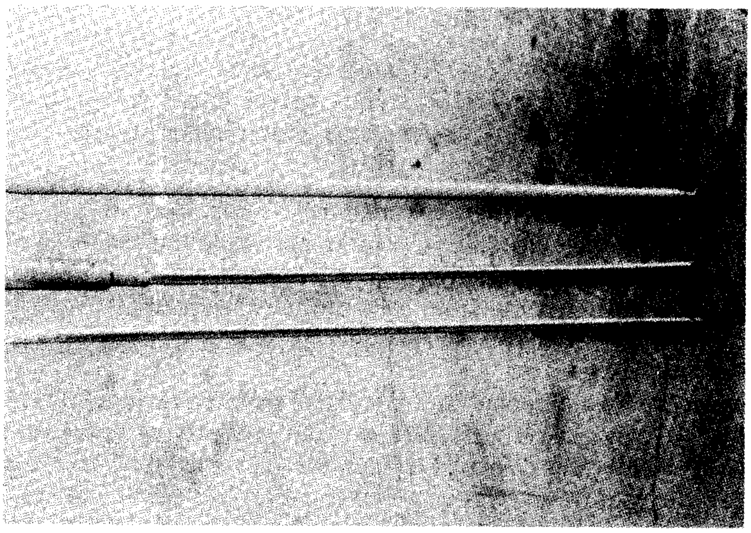


Figure 2. Scaling bars investigated in this study.

Table 1. Scaling bar characteristics.

Bar type	Length (cm)	Weight (kg)	Circ. (cm)	CG from operator's end (cm)
Standard	248	4·26	12·2	137·16
Ctr-bal	248	3·99	8·4	74·93
Light	248	1·72	8·0	153·04

subject while performing the task. Knee pads were worn during conditions requiring kneeling postures.

2.4. *Procedure*

Subjects were brought into the laboratory and prepared for EMG recording. The six muscles listed above were identified and the skin prepared in order to obtain suitable signals using standard EMG preparation techniques (Marras 1987). Bipolar surface electrodes were placed on each muscle and connected to miniature preamplifiers worn by the subject. Each preamplifier was connected to a main EMG amplifier and signal filters. The signal was then rectified and electronically integrated with a time constant of 0·1 s. The integrated signal was fed into an analogue-to-digital converter that sampled the signal at 100 Hz. These data were then monitored and stored in digital form on a microcomputer (see figure 3).

Before the experimental session began subjects were asked to produce a maximum voluntary static contraction in each of the muscles of interest. These exertions were performed with the trunk in an upright position which matched the position of the trunk during the performance of the experimental task. EMG activities were recorded during these exertions and the information was used to normalize task EMG data.

Subjects were instructed to perform a scaling task for 4 min in each experimental condition. The task required the subject to strike the dynamometer

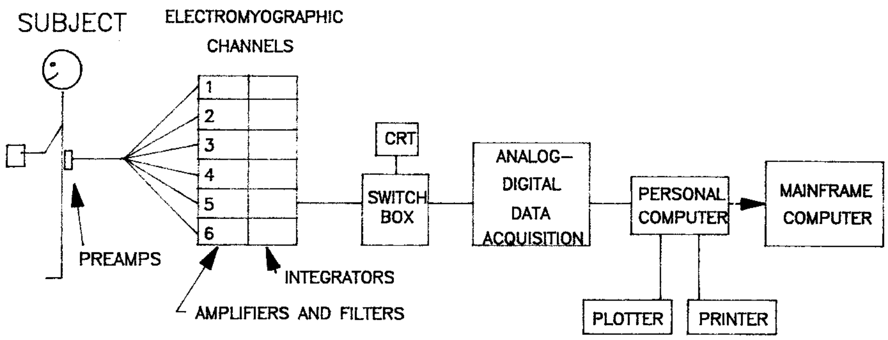


Figure 3. Schematic representation of data collection system.

with the scaling bar and to follow with a prying motion. This is essentially how the tool is used underground. Each strike and pry cycle was initiated with an electronically generated tone every 6 s. Following each 4 min work period, the subject was given at least a 4 min rest period. Before each condition, the subject was instructed as to the method of tool use and the work posture and was allowed a practice session to become familiar with the task. The peak upward and forward components of the strike force were recorded for each strike. The EMG data were sampled on three random strikes for each condition.

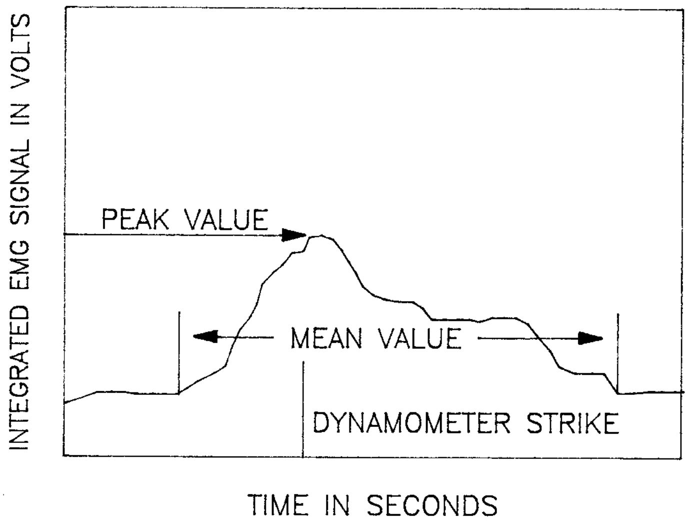


Figure 4. Portions of EMG signal used in analyses.

2.5. *Data treatment*

The EMG signals were analysed for the peak and mean values as shown in figure 4 during the exertion period. Custom software was used to perform this function.

The mean EMG values were averaged within each condition throughout each trial. The EMG value with the largest amplitude throughout the exertion was used to represent the peak muscle activity in the analysis. For each muscle within each subject, EMG values were normalized with regard to the maximum and minimum values for that muscle with the following equation:

$$\text{Normalized EMG} = \frac{(\text{Task EMG—Min EMG})}{(\text{Max EMG—Min EMG})}$$

Maximum values were obtained through maximum voluntary contractions of the muscles measured in postures similar to those required in the task. Likewise, minimum values were measured in a relaxed standing posture.

3. Results

3.1. *Muscle activities*

Separate analyses were conducted on the mean and peak normalized EMG values. In both cases, a multivariate analysis of variance (MANOVA) model including the EMG values from the six muscles was tested. In these analyses the activities of the six muscles were considered collectively. The results of these tests are presented in table 2. Both MANOVAs show the dependent measures to be under the control of the experimental manipulation. Since the design was blocked on subjects and roof height only, the bar-method interaction could be tested. This interaction was non-significant for the mean EMG model and for the peak EMG model. However, the MANOVAs showed all main effects were highly significant. Subsequent ANOVAs for each dependent measure were conducted to evaluate which muscles were affected by the experimental conditions. These were evaluated using an adjusted alpha level (Bon Feroni procedure) of 0·00833. Those dependent measures showing significant differences are presented in table 3. All dependent measures also showed a significant subject effect. Individual differences in activation of muscles would account for these results.

Table 2. Summary of MANOVA results.

Analysis of mean EMG data			Analysis of peak EMG data		
Test	*F* (Wilks*)	Probability	Test	*F* (Wilks*)	Probability
Subject	10·91	p=0·0001	Subject	9·95	p=0·0001
Roof	24·88	p=0·0001	Roof	14·24	p=0·0001
Method	4·38	p=0·0004	Method	2·05	p=0·0628
Bar	4·19	p=0·0001	Bar	3·34	p=0·0001
Method*bar	0·63	ns	Method*bar	0·75	ns

Table 3. Summary of ANOVA significance.

	Significant ANOVAs using mean EMG values				Significant ANOVAs using peak EMG values		
DV	Test	*F* (Wilks*)	Probability	DV	Test	*F* (Wilks*)	Probability
LATR	Bar	16·78	0·0001	LATR	Bar	12·21	0·0001
LATL	Roof	36·00	0·0001	LATL	Roof	12·20	0·0006
	method	15·11	0·0002		bar	8·17	0·0004
	bar	9·20	0·0002				
ERSR	Bar	8·43	0·0003	ERSR	Bar	5·93	0·0033
ERSL	Roof	66·48	0·0001	ERSL	Roof	32·96	0·0001
RCAR	Roof	8·13	0·0050				

Figures 5a–f summarize the nature of the differences observed in this experiment. When the effects of method of scaling bar use on muscle activities were evaluated it was found that only the mean activity in the left latissimus dorsi muscle showed a significant increase with the overhand method (see figure 5a). However, subjects typically complained of muscle fatigue when using this method of scaling.

Changes in roof height conditions differentially affected the muscular activity required from the latissimus dorsi muscles, the left erector spinae muscles, and the right abdominal muscle. These differences are shown in figures 5c and d. Higher roof heights generated significantly more latissimus dorsi and right

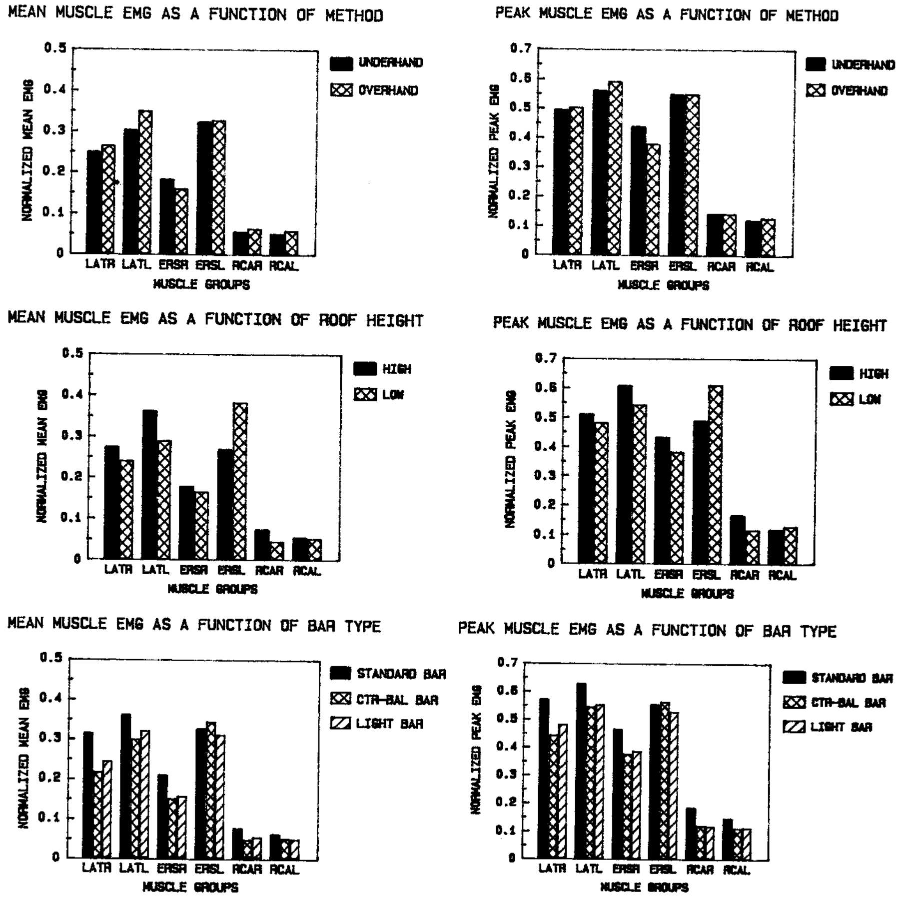


Figure 5. Mean and peak muscle activities as a function of (a) and (b) method, (c) and (d) roof height, and (e) and (f) bar type.

abdominal activation, while the low roof conditions generated significantly more activity in the left erector spinae. These changes may reflect differences in trunk stabilization patterns in the standing versus the kneeling postures.

All bar effects shown in figures 5e and f when tested with a Duncan's multiple comparison procedure show the standard bar to require greater muscular force than either the counterbalanced or the lightweight aluminium bars. This was true for the right erector spinae muscle, and the left and right latissimus dorsi muscles. Tests comparing the resultant strike force by the three types of bars showed no significant differences. The trend showed the standard bar had the highest strike force, followed closely by the counterbalanced bar, with the light aluminium bar having the lowest strike values.

3.2. *Predicted spine forces*

The EMG activities were used as input to the SIMULIFT dynamic biomechanical model developed by Reilly and Marras (1989). Since the experimental conditions required static back exertions, the EMG activities were considered to be related to the amount of force present in the trunk muscles. The

SIMULIFT model was used to study the compressive and shear forces acting on the spine as a function of the experimental variables due to the collective activities of the trunk musculature.

Table 4. Statistical test of estimated compression and shear forces on the spine.

Independent variable	Compress test probability	Shear test probability
Subject	$p<0.0001$	$p<0.0001$
Bar	$p<0.025$	$p<0.0005$
Roof	$p<0.055$	ns
Method	ns	ns
Bar*method	ns	ns

The predicted peak compression and shear forces acting on the lumbar spine were tested for statistical significance between the experimental conditions. The results of this analysis are shown in table 4. This table indicates that a significant change in peak spine compression occurs due to both bar and roof height effects. No statistically significant differences in predicted compression due to method or the bar and method interaction were noted. Differences in predicted compression due to bar types are shown in figure 6. This figure shows that both the light bar and the counterbalanced bar produced lower amounts of predicted spine compression than the standard bar. Figure 7 indicates the effect of roof height upon predicted spine compression. This figure indicates that low roof condition results in approximately a 150 N increase in predicted compression.

Table 4 indicates that the shear forces acting on the spine change as a function of the type of bar only. The trend in shear forces is shown in figure 8. The counterbalanced bar produces less shear than either the standard or the light bar.

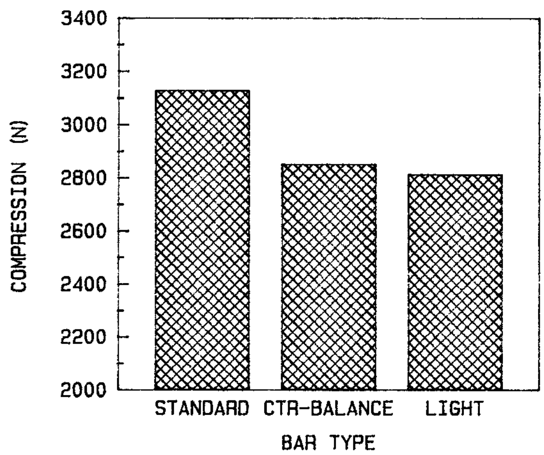


Figure 6. Predicted spine compression as a function of type of bar.

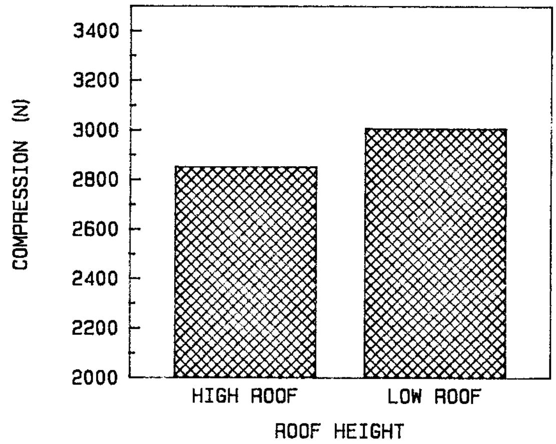


Figure 7. Predicted spine compression as a function of roof height.

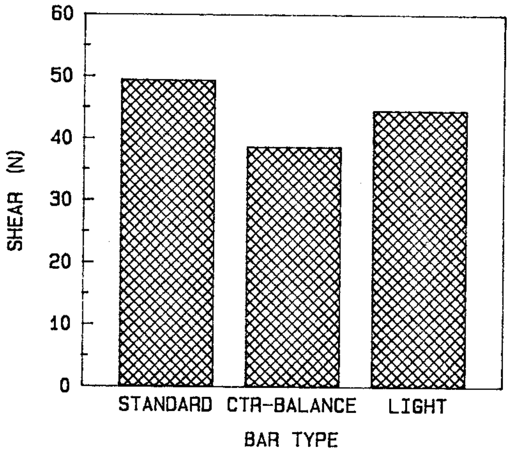


Figure 8. Predicted spine shear as a function of type of bar.

3.3. *Striking force*

The relative differences in peak load cell strike forces are shown in figure 9. Even though these results are not significantly different, it is clear that the standard bar and the counterbalanced bar produce greater amounts of force. It is interesting to note that the tool forces are comparable between the standard and the counterbalanced bars, and the predicted spine forces are lowered with the light and counterbalanced bar. Thus, the cost of doing work (to the spine) is lower when the nonstandard bars are used to perform the scaling task.

4. Discussion

The results described above illustrate the effects of bar type, roof height, and scaling method on the muscular activities required to perform the scaling task. Method had the least effect on the muscle activities with the exception of the left latissimus dorsi. This is not surprising since the difference in the two methods

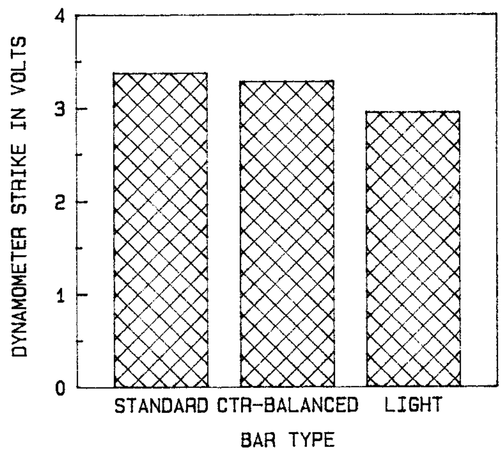


Figure 9. Striking performance as a function of bar type.

focuses on the posture of the left arm during the scaling task. Abduction of the left shoulder would generate a larger external moment to be counteracted by the musculature. As mentioned above, the overhand method was not preferred by our subjects, who typically complained of fatigue in the shoulder muscles following sessions employing the method. This method is thought to protect miners from debris sliding down the bar. Most miners interviewed underground expressed the opinion that this was not a frequent problem.

The elevation in muscular activity in the left erector spinae with lower roof heights is thought to represent the increased moment about the spine due to the fact that the bar must be held at a greater angle from the spine during use under these conditions. This is consistent with the increased erector spinae activity reported by Gallagher (1987) and Gallagher *et al.* (1988) when investigating the physiological demands of the kneeling work posture. In both postures, the required motion was asymmetric, as shown in the elevated activity of the left latissimus dorsi and erector spinae musculature relative to the corresponding right musculature. However, when in a kneeling posture, subjects are forced to make even more of an asymmetric motion with the torso since no twisting motion can occur at or below the pelvic level. This increased EMG activity in the left erector spinae and possibly the slight decrease in the right erector spinae EMG activity can be attributed to this motion. In the standing posture, the load tends to be compensated for with the latissimus dorsi muscles, possibly the right erector spinae and probably some motion in the pelvis.

The lack of a significant difference in the strike force imparted by the three types of bars, along with the reduced muscle activity seen in the light and counterbalanced bars, suggest that bar design may be important. The most frequently observed bars in our visits underground were made of old drill steel. The weight of a bar constructed of this material and of similar length to those used here would exceed that of the standard bar. The results of the present study indicate that the weight of the bar is not necessarily a determinant of its effectiveness. Hence, lighter bars, possibly using a counterbalance, would maintain effective scaling and would bring the external load closer to the spine. This decreases the moment arm and therefore the compressive forces acting on the spine. Following the experiment, subjects gave the counterbalanced bar the most favourable evaluation, thereby suggesting this as a direction for further investigation of scaling bar design.

The biomechanical evaluation of spine loadings also confirms this logic. The predicted spine force analyses indicated that the counterbalanced and light bars produced the least amount of force on the spine. This is particularly significant when considered in conjuction with the fact that there is little difference in the amount of force one can generate using the various tool designs. Thus, these biomechanical analyses indicate that the use of alternative scaling bar designs in the work place can significantly reduce the risk of a low-back disorder due to cumulative trauma. This is of utmost importance since it is believed that it is the repetitive wear and tear upon the spine (cumulative trauma) that poses the largest risk of injury. Reduction of spine forces by even a small amount (i.e., 150 N due to spine compression) can result in a substantial savings in spine wear and tear as well as lost time when the daily, monthly, and yearly frequency of scaling bar use is considered

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