Analysis of applied forces and electromyography of back and shoulders muscles when performing a simulated hand scaling task

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ABSTRACT

Hand scaling is a physically demanding task responsible for numerous overexertion injuries in underground mining. Scaling requires the miner to use a long pry bar to remove loose rock, reducing the likelihood of rock fall injuries. The experiments described in this article simulated "rib" scaling (scaling a mine wall) from an elevated bucket to examine force generation and electromyographic responses using two types of scaling bars (steel and fiberglass-reinforced aluminum) at five target heights ranging from floor level to 176 cm. Ten male and six female subjects were tested in separate experiments. Peak and average force applied at the scaling bar tip and normalized electromyography (EMG) of the left and right pairs of the deltoid and erectores spinae muscles were obtained. Work height significantly affected peak prying force during scaling activities with highest force capacity at the lower levels. Bar type did not affect force generation. However, use of the lighter fiberglass bar required significantly more muscle activity to achieve the same force. Results of these studies suggest that miners scale points on the rock face that are below their knees, and reposition the bucket as often as necessary to do so.

1. Introduction

The roof and ribs (i.e., walls) of underground mines are regularly examined and scaled with a long pry bar to remove loose surface rock. The purpose of this activity is to reduce the likelihood of rock fall injuries and is a safety activity mandated by the U.S. Mine Safety and Health Administration (MSHA). Hand scaling is a physically demanding task, and is associated with numerous overexertion injuries. Two-thirds of scaling-related overexertion injuries involve the back and shoulders with the major injury being a pulled back muscle (MSHA, 2000–2004). The average number of lost days per scaling overexertion injury was 65 days compared to 28 days lost on average for scaling-related injuries as a whole.

In many high-seam mines (such as underground limestone or salt mines), scaling of the mine ribs (i.e., mine wall) requires miners to work from an elevated bucket, positioned a few feet from the rock face. The distance between the bucket and the rib varies depending on how close the bucket can safely be positioned to the rib. Occasionally two miners may be scaling from the same the bucket. The scaling process starts with a visual inspection of the rock face to locate cracks or other signs that a rock must be removed. The miner then uses a scaling bar to probe any observed cracks for loose rock by jabbing the tip of the scaling bar into the crack to determine whether the tip can obtain enough purchase to remove a piece of loose rock. Removal is achieved by applying a downward shear force often combined with a prying motion to pull the loose rock away. Field observations of this task showed that once the bucket has been positioned, the miner(s) tend to start scaling at shoulder level and work downward, and that the bucket is usually not moved until the miners have scaled everything they can reach from their current position.

Previous research on the physical demands of scaling bar use is scant. Marras and Lavender (1991) examined overhead roof scaling using different weights and types of scaling bars. Their study based recommendations on predicted spine compression forces and striking force at the tip of the scaling bar. The authors found predicted spine forces lower for the lighter bar which gave slightly lower average striking force, but this difference was not statistically significant. It was also found that a counterbalanced scaling bar (with more bar weight closer to the operator) significantly reduced low back loading. However, this research looked only at overhead scaling bar use and not wall-scaling activities, for which physical demands would differ considerably. Therefore the goal of the present investigation was to evaluate the force generation capabilities and electromyographic responses to simulated rib scaling exertions in a laboratory setting. Specifically, the focus of these studies was the downward force application since the maximum effort occurs during this subtask. Improved knowledge of the

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physical demands and worker capabilities associated with this scaling task should allow better recommendations for appropriate work height, bar type and bucket position to reduce overexertion injury risk.

2. Methods

2.1. Subjects

A total of sixteen subjects (10 males and 6 females) were tested. The male subjects had a mean age of 46.1 years (SD = 6.4) and the female subjects had a mean age of 37.3 years (SD = 11.3). Two of the male subjects had previous experience with hand scaling in a mining environment; none of the females had such experience. Subjects in both studies were volunteers and operated under terms of informed consent. Male subjects had a mean height of 180.3 cm (SD = 3.8 cm) and a mean weight of 90.5 kg (SD = 10.28 kg). The female subjects had a mean height of 163.8 cm (SD = 15.22 cm) and a mean weight of 68.6 kg (SD = 10.58 kg). All subjects except for one female were right hand dominant. However, this subject also indicated that she played sports right handed and, for consistency, was asked to perform the task in the same manner as the other subjects. Prospective subjects were excluded if they had not completely recovered from prior musculoskeletal injury, or if any other medical condition contraindicated their participation.

2.2. Experimental design

Testing of the male and female subjects were considered separate studies, but both employed the same experimental paradigm. Two independent variables, the height of the target on which the force was generated (five levels) and the scaling bar type (two levels), were investigated. Dependent variables consisted of peak and mean downward force (in Newtons) generated by the subject against a uni-axial dynamometer at five specified target heights (THs), and peak and mean normalized surface electromyographic (EMG) activities from four muscles as detailed below (Keppel, 1991; Kirk, 1995). As discussed previously, the predominant injuries observed in scaling bar tasks were injuries to the back and shoulder. For this reason the authors examined the activity of muscles that were most related to injury mechanisms of those joints. The muscles selected were the erectores spinae (the primary loader of the low back) and the medial head of the deltoid (an important anterior stabilizer of the shoulder joint).

A split-plot experimental design was used where subjects were treated as whole plots (with target height treated as main plot factor), and scaling bar type constituted the sub-plot factor. This design required two separate randomizations within each subject. First, randomization of the target heights was performed, and within each level of this variable a restricted randomization of scaling bar type was performed. Three replications of each combination of target height and bar type were executed, for a total of 30 trials per subject (Keppel, 1991; Kirk, 1995). The data from the replications were combined for the analysis.

2.3. Procedure

EMG electrodes were placed on the skin's surface above the medial divisions of the left deltoid (LD) and right deltoid (RD), along with the left erectores spinae (LES) and right erectores spinae (RES) muscle groups (L3 lumbar level). The signal was collected at 1000 Hz and amplified using a low noise instrumentation amplifier with a common-mode rejection ratio of 110 dB. All EMG signals were processed using a high-pass filter to remove potential motion artifacts in the form of frequencies below 20 Hz and a low-pass filter to remove unwanted frequencies above 450 Hz. The EMG signal for each muscle was normalized to signals obtained during maximal voluntary contractions (MVC). For the back muscles, the MVC consisted of an isometric trunk extension against resistance from a flexed posture. For the deltoids, the MVC consisted of shoulder abduction against resistance.

A force gauge was mounted on a wall at one of five heights, as illustrated in Fig. 1. The subjects were standing at a horizontal distance of 183 cm from the force gauge. The minimum horizontal distance was determined by the distance that must be maintained to keep the miners safe. This distance was chosen based on field observations of the task made by NIOSH researchers and represented a worst case scenario. The five vertical THs of the force gauge were 0, 56, 107, 144, and 176 cm. The upper four heights roughly correspond to the average knee, waist, shoulder and stature for a 50th percentile male and 95th percentile female. Females were tested at the same heights since females may be required to scale at similar heights to males if working in tandem in an elevated bucket. Since the female subjects participating in this study were about 50th percentile in height, the authors acknowledge that the female subjects were at a biomechanical disadvantage at the higher THs as compared to the male subjects, and that this disadvantage could affect the results of this study.

Two types of scaling bar (SB) were tested: one made of steel, the other consisted of a hollow aluminum pipe reinforced with fiberglass. Marras and Lavender (1991) identified the common length of the bars to be 245 cm long, so this bar length was used in this study. The steel bar weighed 6.4 kg with a diameter of 2.5 cm and a deflection upon load of 15 mm, while the fiberglass bar weighed 4.0 kg with a diameter of 4.0 cm and a deflection upon load of 6 mm. The deflection upon load of the scaling bars was found by supporting the bar at both ends and applying a 23 kg load to the middle of the bar and measuring the deflection of the bar from resting position. Both bars ended in a straight chisel tip.

To ensure correct placement of the bar, the tip was placed on the dynamometer by researchers before each test. Subjects' hand placements were not restricted and they were allowed to hold the bar as they typically would for a similar task. The subjects were not allowed to move their hands during the individual trials. During testing, little variation in subject hand placement was observed. Typically, the subjects would grasp the bar with their dominant (right) hand near the end of the scaling bar and the other (left) hand around the mid-point of the bar. Subjects were then asked to apply

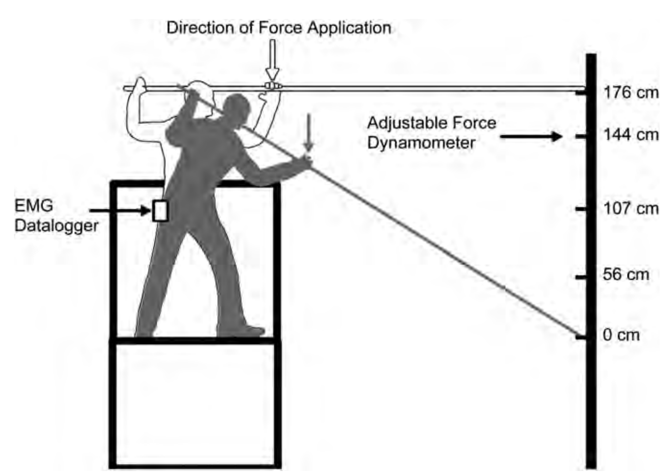

Fig. 1. Experimental setup. Gray figure represents approximate subject posture at the lowest TH; outlined figure represents approximate subject posture at the highest TH. Forces were not measured at the hands, but were predominantly in a downward direction.

a downward maximum voluntary isometric muscular force in accordance with standard isometric strength testing procedures, with 2 min of recovery time given after each trial (Caldwell et al., 1974). The subjects were asked to apply a force for a total of five seconds. The force applied over the last three seconds of the trial was averaged to find the mean force per trial. The peak force was determined as the maximum force over the same three seconds. EMG data were collected and analyzed for the matching three second period of time. Despite the difference in target heights, the subjects' trunk postures were not observed to vary substantially during the performance of the scaling tasks tested.

2.4. Data treatment

Due to the differences in shoulder strength among males and females, it was decided to analyze male subjects and female subjects separately (Chaffin et al., 1999). A split-plot analysis of variance ($\alpha = 0.05$) was used to determine the effect of the independent variables on the peak and mean downward force generated and peak and mean normalized EMG data. Orthogonal polynomials were used for *a posteriori* tests for trends in force as detailed in the results section. The Dunn-Šidák procedure was used for the *a posteriori* tests to maintain an experiment-wise error rate of $\alpha = 0.05$ (Kirk 1995).

3. Results

3.1. Experiment 1: male subjects

3.1.1. Force generation

Inspection of both peak and mean force data for male subjects (Fig. 2) provided strong evidence of U-shaped (quadratic) trends as a function of target height, with higher forces observed at target heights of 0, 56 and 176 cm, and lower values at the intermediate heights (107 and 144 cm above floor level). Accordingly, *a posteriori* trend analysis procedures were used to test for the significance of the suspected trends. The Dunn-Šidák procedure was employed to examine whether significant quadratic, cubic, or quartic trends existed as a function of TH (Kirk 1995). The critical *tDS* for 4 orthogonal polynomial contrasts with $\alpha = 0.05$ and 60 error *df* was 2.653. The obtained *tDS* statistic for a quadratic trend for mean force was 2.740 ($p < 0.05$), and for peak force the obtained statistic was 3.271 ($p < 0.01$), both indicative of significant quadratic trends. Cubic and quartic components were not significant ($p > 0.05$). On average (across all male subjects and target heights), peak and mean forces generated using the two bars were all within a range of 1 N.

3.1.2. Electromyography

The type of bar used during the prying task was found to significantly affect muscle activity in the male subjects, but the height at which the task was done was not significant ($p > 0.05$). For this reason, muscle activation data were aggregated over the heights and analyzed with respect to bar type. Separate analyses were performed on the mean and peak normalized EMG data.

The effect of bar type on mean muscle activity is shown in Fig. 3. Subjects demonstrated 10% greater mean muscle activity in the left deltoid ($F_{1,245} = 9.41$, $p < 0.01$) and the right erector spinae muscle ($F_{1,245} = 14.86$, $p < 0.0001$) with the fiberglass bar requiring increased activity compared to the steel bar. Fig. 4 illustrates a significant interaction between bar type and work height for mean muscle activity of the right deltoid ($F_{4,245} = 2.45$, $p < 0.05$). The right deltoid was significantly ($p < 0.05$) less activated at THs of 56 and 176 cm when using the steel bar (TH 176 cm contrast 6.15; $F_{1,245} = 7.26$, $p < 0.01$; TH 56 cm contrast 7.05; $F_{1,245} = 5.89$, $p < 0.05$). This interaction may be due to postural changes at these two levels or differences in bar properties at these levels. Peak muscle activity data, like mean data, demonstrated subjects experienced significantly greater muscle activity for both left ($F_{1,245} = 7.21$, $p < 0.01$) and right deltoids ($F_{1,245} = 12.06$, $p < 0.001$) when using the fiberglass bar rather than the steel bar.

3.2. Experiment 2: female subjects

3.2.1. Force generation

Female subjects were affected by a significant interaction between TH and SB for both peak ($F_{4,145} = 3.35$, $p < 0.05$) and average ($F_{4,145} = 4.27$, $p < 0.01$) force. Fig. 5 illustrates the interaction for peak force. The peak force generated using the fiberglass scaling bar showed a tendency towards the quadratic trend exhibited by males. However, force generation varied considerably with the steel bar for female subjects. Using the steel bar at floor level resulted in the greatest force production overall for female subjects. Peak forces at the 56 and 107 cm THs were nearly identical for both bars. However, at the upper two THs, the steel bar and fiberglass bar reversed in terms of force production, with the steel bar having the advantage at the 144 cm TH, and the fiberglass bar superior at the 176 cm TH. Mean forces for the females followed the same trend as the peak forces but were approximately 5 N lower.

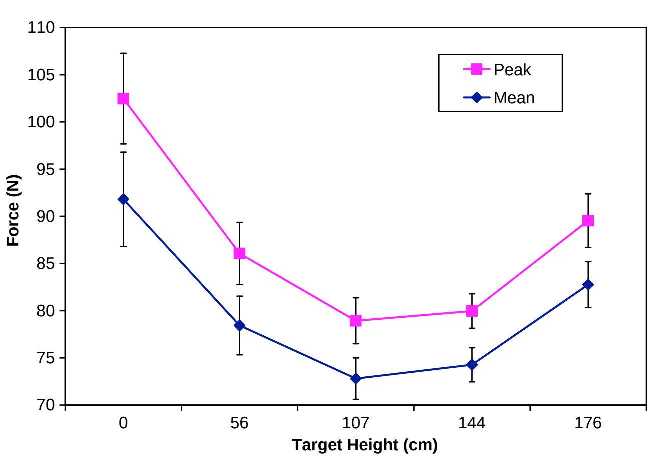

Fig. 2. Downward force generated as a function of work height for male subjects ($n = 10$) (bars represent standard error of the mean).

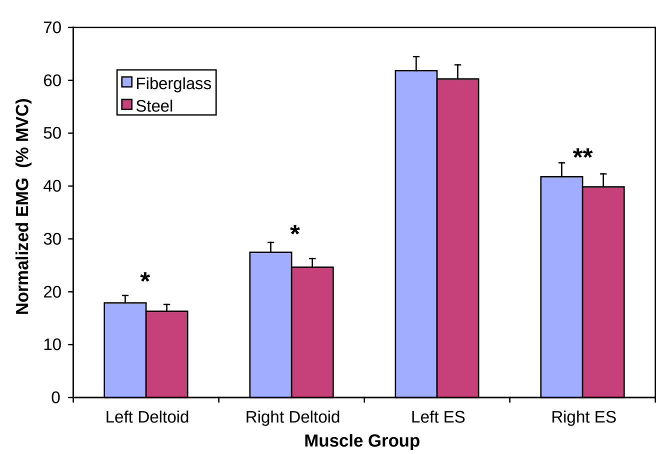

Fig. 3. Mean normalized EMG data as a function of bar type for male subjects ($n = 10$) (bars represent standard error of the mean) (* significant difference at $p < 0.01$; ** significant difference at $p < 0.001$).

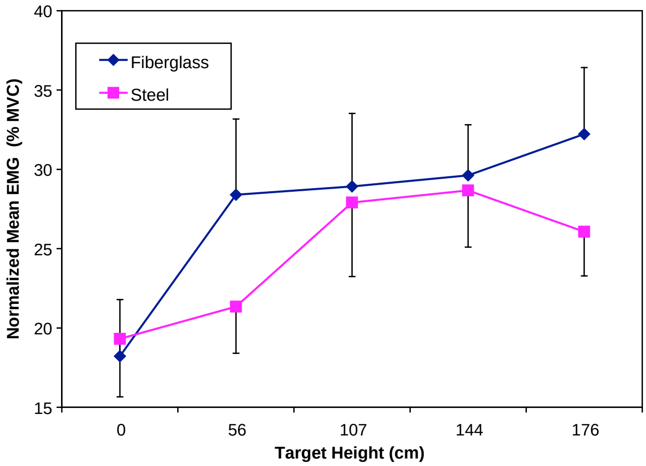

Fig. 4. Interaction effect of the average right deltoid normalized EMG for male subjects ($n = 10$) (bars represent standard error of the mean).

Forces generated by females were approximately 65% of the force generated by males. This percentage was consistent for both peak and mean force measures.

3.2.2. *Electromyography*

The right deltoid was the only muscle to be significantly affected by any of the independent variables for female subjects. The peak and mean activities were affected similarly for all THs and SB. Peak activity of this muscle was significantly affected by TH ($F_{4,20} = 4.03$, $p < 0.05$). This effect was characterized by a significant increase in activity at the 107 and 144 cm THs compared to other THs (Fig. 6). Average activity of this muscle was affected by an interaction of TH and SB ($F_{4,145} = 4.53$, $p < 0.01$). The activity associated with the use of both scaling bars increased at the 107 and 144 cm THs; however, the interaction appears to have been driven by higher average deltoid activity at the lower heights for the fiberglass bar than for the steel bar.

Comparison of EMG activity between males and females indicated two primary differences. Males tended to exhibit increased higher normalized mean activity in the RES compared to females (41% versus 21%), while females exhibited increased mean activity in the RD (44% versus 26% for men). These differences in muscle activation were consistent across THs and SBs. Activation of other muscles was found to be similar (within 5%) for both genders.

4. Discussion

The objective of this study was to investigate the force generation capabilities and electromyographic responses to a simulated hand scaling subtask. Results from the study with the male subjects demonstrated that force generation capability was a function of TH and muscle activity was primarily a function of bar type. Specifically, TH was found to significantly affect the maximum amount of force males generated during this simulated scaling task. This study indicated reduced capacity in downward force production when the target height was located around the torso region, with higher force generation when the target was at higher or (particularly) lower levels. The higher forces at lower heights may be attributed to application of the weight of the body (leaning into the bar) to increase force generated, while higher forces at the 176 cm TH may be attributed to "hanging" on the bar with the forward arm to increase the amount of force exerted. Around the torso region (with a fairly "level" orientation of the scaling bar), subjects could not effectively use their body weight to generate additional force with the bar, resulting in reduced capacity. As noted in the results section, increased muscle activity of RD was increased for THs in this region for males, yet was unable to result in higher forces generated at the scaling bar tip. Thus, it appears that target heights around the waist to shoulder region have a dual penalty with respect to rib scaling: increased required muscle activity (evident in both genders), yet decreased force output at the scaling bar tip (particularly evident in males).

Force generation by females was a product of both SB type and TH, which though significant, was not easy to interpret. The greatest force capability demonstrated by females was consistently the steel bar at floor level, with all other conditions resulting in forces within a fairly narrow range and no clearly discernable trend. Differences in force generating capabilities between genders in this scaling task coincides with data from previous studies indicating an overall strength deficit for females compared to males (Astrand and Rodahl, 1977). In general, the muscle strength of an adult female is lower than that of males for all muscle groups, with the muscle strength of females approximately two-thirds that of males (Stobbe, 1982; Roebuck et al., 1975), which is almost precisely the difference in force generation observed in the present study. Scaling may be particularly demanding for females due to high requirements on the shoulder muscles, where a greater difference in strength between men and women typically exists (Kuhlman et al., 1992; Mayer et al., 1994; Amell, 2004). The fact that women will be working at a higher percentage of shoulder strength

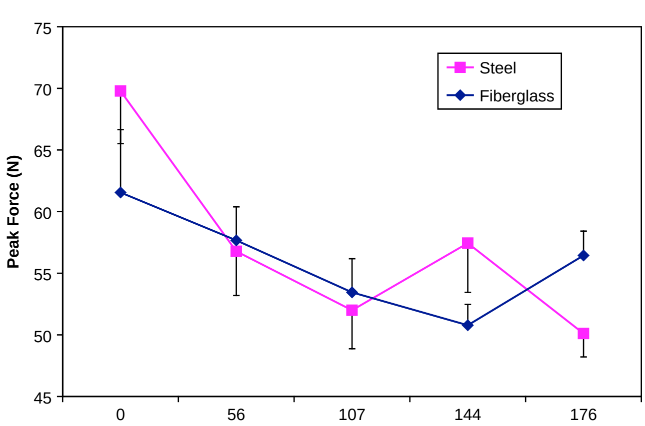

Fig. 5. Peak downward force generated by female subjects by THs and SB ($n = 6$) (bars represent standard error of the mean).

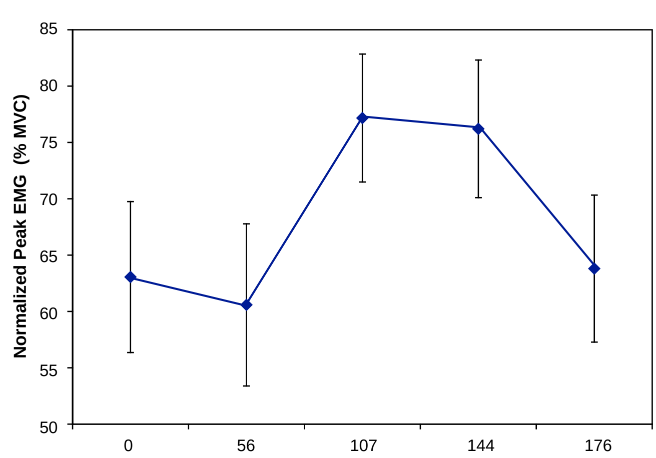

Fig. 6. Peak right deltoid activity for female subjects by height ($n = 6$) (bars represent standard error of the mean).

capacity may help explain higher muscle activity observed for the right deltoid, which was required to hold up the near end of the bar and keep it stabilized while exerting force. The force data from the female subjects is difficult to interpret due to the presence of a significant interaction. The main finding was that their force responses were influenced by both TH and SB and were a function of the specific combination of these factors.

When one considers the typical procedure for scaling outlined in the Introduction (where miners typically start scaling at shoulder height and work their way down), it would appear that the current procedure puts the miner at a significant disadvantage at the start of the scaling operation until the miner can get to locations that are at or below knee height. Force generating capacity appeared related to the ability to use mechanical advantages such as body weight. This may be particularly important for females, who exhibit an overall strength disadvantage. The highest average peak force of approximately 70 N for females was at the 0 cm TH. This value was just slightly higher than the force of gravity on the steel scaling bar used in this study.

The results of these studies lead to the conclusion that miners should scale points on the rock face that are at or below their knees and reposition the bucket as necessary to accommodate that work height region. While higher force capacity was observed at a TH of 176 cm, the act of scaling at that level requires a miner to manipulate the bar substantially more than at lower THs, which could introduce additional joint forces and awkward postures. It must be recognized that two miners may be in the same bucket so coordination of the bucket movement is a critical aspect of this recommendation.

The type of bar used, for the male subjects, was not found to affect the force generated at any heights tested. However, increased muscle activity was required to generate the same amount of force with the lighter fiberglass bar as opposed to the heavier steel bar for the male subjects. A heavier bar may necessitate more muscle activity to hold, lift, and control the bar if the entire task is considered. For the subtask studied, results from the male subjects suggest that if a miner needs to utilize a tool to exert a force, a lighter tool may actually require increased muscle activity to reach the same force level generated by a heavier tool. Thus, in the case of the subtask under study, the heavier tool may actually confer a biomechanical benefit thereby reducing the stresses on the body. In addition, the greater deflection of the steel bar may have assisted in transferring a greater compressive force to the dynamometer. Proper evaluation of the trade-offs associated with tool weight will require additional research. Indeed, it may be necessary to use both types of bars and even several different lengths of bar to reduce the stress placed on the body given the variety of circumstances that may be encountered while hand scaling. More research on scaling tasks and the effects of flexibility, length, size, diameter, and weight of various bar types must be completed to offer comprehensive recommendations.

Previous research on scaling bars, as discussed in the Introduction, found that predicted spine forces were lower for the lighter bar and gave slightly lower average striking force. The results of the current study indicated that it was more difficult to get the same downward force when using the lighter bar. Subjects had to work harder as indicated by the increased muscle activity to accomplish the same task when using the lighter bar. The discrepancies in the two findings are probably due to the difference in the subtasks examined.

4.1. Limitations

Certain limitations need to be considered when evaluating these data. While the experiment helps define the capabilities of miners to generate forces using a scaling bar, certain other aspects of the task (such as jabbing of the rock wall) were not able to be accurately replicated with the current experimental setup. Potential damage to the dynamometer from such activities was a concern to the investigators. Further, the subtask studied in this experiment is not representative of the overall demands of scaling since scaling requires multiple subtasks varying in posture, actions, and force. While the heavier bar seemed to confer some advantages in the current experiment in terms of reducing muscular demands for the experimental task, clearly this advantage may be outweighed in other situations such as carrying or lifting the bar for overhead scaling.

The choice of bars used in this study may also be a limiting factor in the generalization of these results. The bars that were identified as most common had not only weight differences but also differences in diameter and deflection upon load. Each of these variables would have an effect on strength observed. For this reason, the results can not be easily distinguished between bars characteristics; instead only the overall bar effect can be discussed. Force generating capacity of a scaling bar may also be a function of the bar length and horizontal distance from the subject to the target. These variables were not examined in this study for simplicity of the experimental design.

Finally, it was decided to test females at the same THs as males for comparative purposes; however, these heights probably disadvantaged females, particularly at the highest TH. At this TH the female subjects were working above their heads; this would mean that the shoulder and mid back muscles would be more active. Since these muscles were not monitored in this study, the authors could not make definitive conclusions on how females responded to scaling at this level. The trends identified for the males were not seen for the females; this is possibly due to the varied regional strength differences of males and females (Chaffin et al., 1999).

Additional research will be necessary to develop comprehensive work practice recommendations that address (in a more holistic way) the goal of reducing the injury risk to miners when performing hand scaling activities.

5. Conclusion

Results of this study support the following conclusions:

1) The height at which the scaling bar tip is positioned has a significant impact on peak and mean force generation capability for male subjects and follows a U-shaped curve with highest values for targets at or below 56 cm (knee) height and lowest values in the 107–144 cm (waist to shoulder) region.
2) Peak and mean force generation by females was affected both by the height of the scaling target and the bar used. Greatest forces were generated using the steel bar at a target height of 0 cm (floor level) for the females, for both peak and mean force data. The female subjects exhibited a similar, but not significant, quadratic trend demonstrated by males when using the fiberglass but not the steel scaling bar.
3) The type of scaling bar (steel or fiberglass) did not affect forces applied for the males; however, these subjects showed increased EMG activity for the right erectores spinae and left deltoid when using the lighter fiberglass bar. For the female subjects, no specific scaling bar effect independent of target height was identified.
4) Female subjects were able to generate approximately 65% of the force of males at the scaling bar tip. Analysis of muscle recruitment indicated higher activity of the right erectores spinae for males as compared to females and increased activity of the right deltoid muscle in females as compared to males.
5) Results of this study, for both males and females, suggest that repositioning the bucket to allow for scaling of rock at or below

56 cm (knee level) would be advisable due to the decreased force generation capacity when scaling at higher target heights. If two miners are in the bucket, position the bucket according to the height of the shorter miner or have the taller miner scale at higher locations particularly when scaling near the roof.

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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