A BIOMECHANICAL ANALYSIS OF A BOLTER CABLE PULLING TASK

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Seven experienced miners performed a bolter cable pulling task while ground reaction forces and cable tension were measured. The independent variables were two levels of cable resistance (low and high) and lifting conditions (kneeling, stooping under a 1.2 m [48"] roof, stooping under a 1.5 m [60"] roof, and unrestricted standing). Work posture significantly affected the peak cable tension and the peak shear force resultant angle. These variables were highest in the kneeling condition, indicating that there is less postural stability when performing cable pulling tasks in a kneeling posture. Thus, there may be a greater likelihood of injury due to increased muscle forces or slips and falls in this posture. Therefore, it is imperative that engineering controls be utilized to minimize the amount of cable handling tasks that need to be performed.

INTRODUCTION

The height of an underground coal mine is generally determined by the thickness of the mineral seam. About half of the coal seams in the United States are below 1.2 meters (48 inches) in thickness. Furthermore, as the mineral reserves are depleted, mining in these low seams will become more common. Because of the restricted roof heights, miners are often forced to adopt restricted postures during their work activities, and these restricted postures undoubtedly are a major factor in the high incidence rate of musculoskeletal injuries in the mining industry. According to Bobick (1987), the two most common postures used by miners who work in low coal are stooping and kneeling on two knees.

One particularly stressful task performed in underground coal mines is the manual handling of the electrical cables which are used to power the mining equipment. In order to keep the cable from being run over and destroyed, it must frequently be pulled and hung as the cutting face advances and the mining equipment moves. According to one Bureau of Mines analysis of accident data (Randolph, 1991), miners who perform these tasks, namely continuous miner operators and continuous miner helpers, account

for about 24 percent of lost time back injuries, even though they account for only 9.2 percent of the underground coal mining population.

Hence, biomechanical analyses which examine the stresses associated with cable handling being performed in restricted postures, as well as unrestricted postures, are necessary in order to document the hazards associated with these tasks. Work procedures and work methods can then be recommended based on these analyses so that the biomechanical risk factors associated with back injuries can be minimized in the underground mining work environment.

One task which must frequently be performed by coal miners is that of manually pulling or dragging the bolter cable out of the way of moving equipment. In addition, some states and some companies require miners to pull bolter cable from the reel in order to inspect it for damage. This study begins to examine the biomechanical stresses associated with cable pulling by simulating the job in a laboratory setting and measuring the ground reaction forces while miners perform this task. This study is part of a series of tests conducted by the Bureau examining the biomechanics of cable handling.

METHOD

Subjects

The sample consisted of seven healthy male subjects with coal mining experience. (Age = 41.4 years ± 2.1 s.d., Weight = 80.0 kg ± 14.5 s.d., Stature = 171.4 cm ± 3.6 s.d.) All subjects were paid volunteers who operated under terms of informed consent. Prior to testing, each subject received a thorough medical examination and a graded exercise tolerance stress test to determine if any medical problems exist that would preclude the use of the subject in the study.

Experimental Design

The independent variables in this experiment were four levels of posture and two levels of cable pulling resistance. The four levels of posture were: kneeling, stooped under a 1.2 meter (48") roof, stooped under a 1.5 meter (60") roof, and unrestricted standing. The two levels of cable pulling resistance were: low -- pulling a cable attached to a 20 kg (44 lb.) load, and high -- pulling a cable attached to a 25 kg (55 lb.) load. Thus, there were eight conditions, and each subject completed all conditions. The dependent variables were the peak values of the following: actual tension measured in the cable, ground shear force resultant vector (magnitude and direction), the magnitude of the total resultant force vector, and the required coefficient of friction. A within-subjects split-plot design was used, and the order of treatments was randomized for each subject (Meyer, 1989).

Apparatus

The layout of the apparatus is displayed in Figure 1. Two AMTI[1] biomechanics platforms (Model Numbers OR6-5-1 and OR6-6-1) were used to measure ground reaction forces during the cable pulling tasks. Vertical space constraints were controlled by a plywood roof which could be adjusted to the desired height. The cable used in the study was 3.0 cm (1.2 inches) in diameter and is the type actually used to power roof bolting machines in underground coal mines. The cable was attached to a wire that ran through two pulleys so that a bucket would be lifted up a 73 degree inclined plane from the floor to a platform that was 68.6 cm (27") from the floor. Thus, the total distance traversed by the cable was approximately 72 cm (28"). The cable was oriented at an angle of 19.4

[1]Reference to specific products does not imply endorsement by the Bureau of Mines.

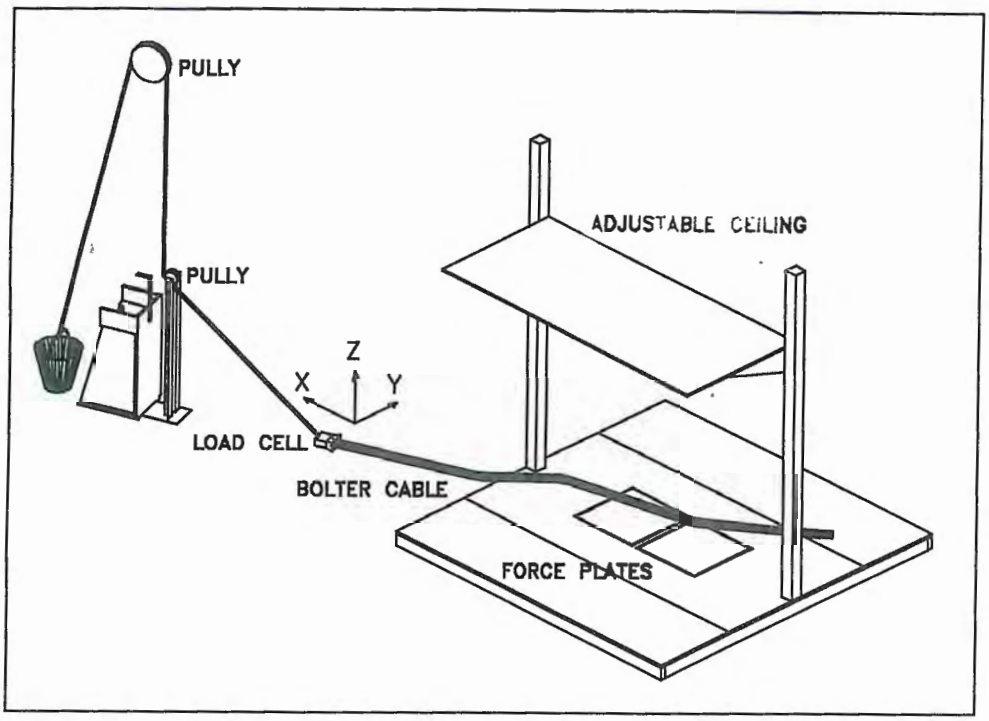

Figure 1. Laboratory Apparatus.

degrees from the horizontal and attached to the pulley at a height of 89 cm (35"). This height is the approximate height the cable attaches to the reels of roof bolting machines. Weights were placed inside the bucket to control the amount of resistance; the mass of the bucket with the weights was 20 kg (44 lbs.) for the low resistance condition and 25 kg (55 lbs.) for the high resistance condition. The force plate and cable tension data were collected with an analog to digital connection to a personal computer at a sampling rate of 100 Hz.

Experimental Procedure

Each subject was informed of the nature of the experiment prior to the medical screening process. On the day of testing, the task was again explained, and each subject was given practice trials to become familiar with the task. Then each subject completed the series of eight pulling tasks in random order while data were collected. The subjects were required to stay on the force plates during the entire task and were given a two minute rest period between each condition in order to minimize the effects of muscular fatigue. The integrity of the data was insured by viewing graphical displays of the force plate data after each trial. The subjects wore tennis shoes, stretch pants, and no shirt. In addition, the subjects wore slip-resistant knee pads (like those typically worn by low-coal miners) during the kneeling conditions.

Analysis

The force vectors in each direction were obtained by summing the force vectors from the two plates, essentially treating the two force plates as one large plate. The resultant shear-force vector was then determined over the duration of the lift by taking the square root of the sum of the squares of the X and Y directional force vectors. The

total resultant force vector was determined by determining the square root of the sum of the X, Y, and Z force vectors. The X-Y resultant force directional angle was determined to be the arctangent of the X-force divided by the Y-force. The peak required coefficient of friction was found by dividing the magnitude of the shear force resultant by the vertical (Z) force component. The peak magnitude values were then determined over the duration of the task for the directional and resultant force vectors, as well as the measured cable tension, directional angle, and required coefficient of friction.

These values were subjected to a 4 x 2 (lifting condition x pulling resistance) Analysis of Variance (ANOVA) procedure to determine which of the independent variables significantly influenced the cable tension, coefficient of friction, directional angle, and ground reaction forces. Separate ANOVA's were performed for each of the dependent variables, and a Tukey Honestly Significant Difference (HSD) follow-up procedure, using a rejection level of 0.05, was performed for those independent variables found to be statistically significant.

RESULTS

Table 1 contains a summary of the significant effects for each dependent variable from the ANOVA's. The cell means for peak cable tension and peak angle by posture are presented graphically in Figure 2. Tables 2 and 3 present the cell means for posture and resistance, respectively. No significant interactive effects were found to be present. The follow-up analysis showed that all dependent variables were significantly higher in the high resistance conditions than in the low resistance conditions. This analysis shows that the peak generated cable tensile forces are higher while pulling cable in the kneeling posture than those in the high stooping and standing postures ($p = 0.01$). The increase in tensile forces is about 33.8 Newtons, or about 9.4 percent, higher in the kneeling posture than in the high-stooped and standing postures. The shear force angle generated was 5.4 degrees greater for the kneeling posture than the other postures ($p < 0.0001$).

Table 1. Summary of Significant Effects

Dependent Variable	Posture (P)	Resistance (R)	P*R Interaction
Peak Cable Tension	*	**	
Average Cable Tension	N/S	**	
Peak Resultant Force	N/S	**	
Average Resultant Force	**	**	
Peak X-Y Resultant Force	N/S	**	
Average X-Y Resultant Force	N/S	**	
Peak X-Y Resultant Force Directional Angle	**	*	
Average X-Y Resultant Force Directional Angle	N/S	N/S	
Peak Required Coefficient of Friction	N/S	**	
Average Required Coefficient of Friction	N/S	**	

N/S Not Significant at $\alpha = 0.050$
* $p \leq 0.050$
** $p \leq 0.001$

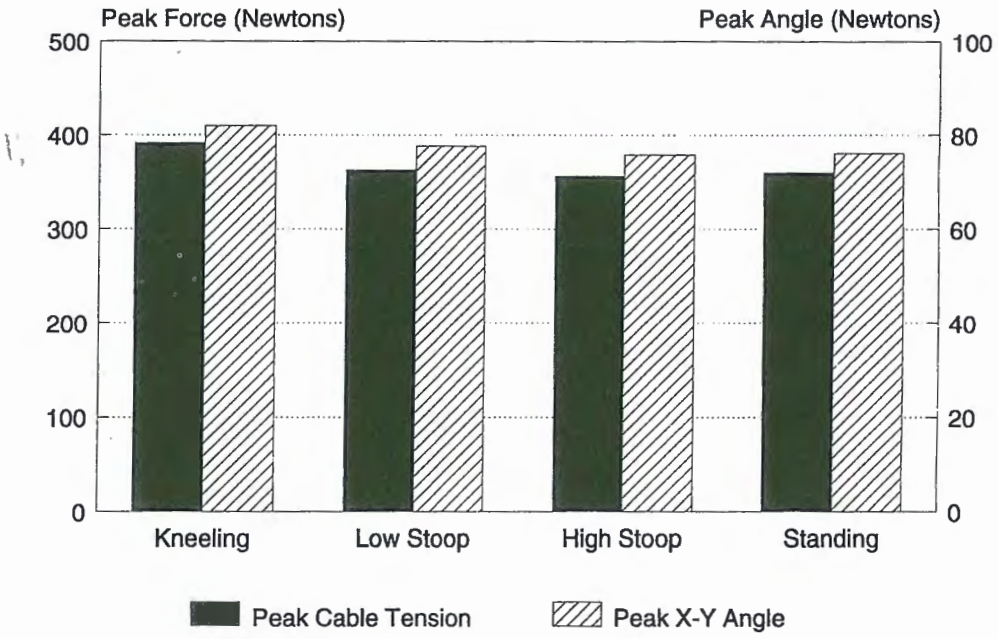

Figure 2. Peak Cable Tension and Peak X-Y Resultant Force Directional Angle vs. Posture.

Table 2. Cell Means by Posture

	Kneeling	Low Stoop	High Stoop	Standing
Peak Cable Tension (N)	391.5	362.2	355.6	359.8
Peak Resultant Force (N)	977.6	971.5	976.8	994.0
Peak X-Y Resultant Force (N)	324.5	329.3	319.3	319.5
Peak X-Y Resultant Force Directional Angle (degrees)	82.0	77.7	75.8	76.1
Peak Required Coefficient of Friction	0.3866	0.3945	0.3722	0.3703

Table 3. Cell Means by Resistance

	Low Resistance	High Resistance
Peak Cable Tension (N)	326.0	408.6
Peak Resultant Force (N)	960.4	1000.0
Peak X-Y Resultant Force (N)	291.4	355.0
Peak X-Y Resultant Force Directional Angle (degrees)	77.1	78.7
Peak Required Coefficient of Friction	0.3501	0.4116

DISCUSSION

The shear force angles generated during kneeling was found to be different from the standing and stooping postures. This difference indicated a different angle of pull during the task. The cable is held more laterally during the kneeling posture. A contributing factor for this change in pulling direction could be the biomechanical requirements of the task. In order to pull the cable, a moment about the base of support must be generated. This moment would be about the Y-axis (the horizontal axis perpendicular to the cable). When the task is performed during standing and stooping postures, the feet provide the base of support necessary to generate a counter moment about the ankles. During kneeling, however, the knees provide the base of support. In this posture there is no anterior lever arm about the joint as there is with the feet in standing. Thus, the is a mechanical disadvantage in the kneeling posture. This finding is consistent with that of Gallagher (1989). To compensate for this disadvantage, the subject must move his/her body center of gravity lower and posterior. This is most easily accomplished by "sitting back" and to the side which changes the angle of pull.

Peak tension in the cable was also found to be significantly affected by posture with the kneeling posture being higher. Subject's tended to jerk the cable at the beginning of the pull when in the kneeling posture which created higher peak forces. This may be due to the restricted pulling distance in the kneeling posture, since the legs are essentially immobilized. Coupled with the subject's difficulty in generating a moment while kneeling, it is not surprising that the subjects chose a strategy of jerking the cable in the initial phase of the pull in order to achieve the necessary momentum to complete the lift.

The increased peak cable tensile forces during kneeling due to jerking the cable also translate to moments generated at other joints in the body. Thus, the low back may have larger impulsive forces and moments applied during the task. Further biomechanical analyses are currently being performed to quantify the magnitude and characteristics of the low back stresses. A dynamic biomechanical model which incorporates the kinematics of movement is being developed to quantify the low back moments. Electromyographic data which was simultaneously collected will then be incorporated into the model to estimate compressive and shear forces as well.

Slipping potentials during cable pulling is another important consideration in the analysis of ground reaction forces. Slips cause acute trauma to miners pulling cables and can also result in unexpected forces and movements on the low back which cause injury (Manning, et al., 1984). Slips occur when the coefficient of friction is greater than the shear force divided by the normal force. The required coefficients of friction in this task

were between .35 and .40. In an actual mining environment, the ground is often slippery due to water or other contaminants. Thus, the results of this study suggest that equipment design (knee pads and shoes) should take into consideration the frictional requirements of the task to prevent slipping injuries.

The preferred method of reducing worker exposure to the risk factors which contribute to occupational injury is by eliminating the need to perform the task. If eliminating the task is not feasible, then the frequency that the task must be performed should be minimized. Certain types of mining equipment and methods help to alleviate the cable handling problem. In the future, alternative power sources may eliminate the need for electrical trailing cables. The use of jacks to guide the cable through cross-cuts can also reduce the amount of cable handling. When cable does need to be moved, a handle with a hook on the end can reduce the need to bend to pick up cable. Finally, if the task must be performed, care should be taken to avoid jerking movements which can contribute to stresses on the joints and the increased likelihood of slips.

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