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Estimating low back loads of underground mine roof bolter operators using digital human simulations

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ABSTRACT

NIOSH researchers conducted a study to evaluate the severity of muscle recruitment and spine loads resulting from performance of the roof bolting cycle in different work postures and mine seam heights. Ten male and two female subjects performed three repetitions of a mine roof bolting in each of seven posture/seam height combinations, while researchers obtained motion data of their actions using a motion capturing system. A database containing forces on L4/L5 spinal joint and on back muscles was generated by processing the captured motions from each subject using UGS PLM Solution Jack software's *task analysis toolkit – lower back analysis*. An analysis of variance was performed using the maximum values for spinal forces and moments and estimated muscle forces for ten trunk muscles in the resulting database. Results of this study indicate that the roof bolter operator's standing posture significantly increases the forward bending moment, compression force and trunk muscle activity more than either kneeling posture. Also the kneeling postures in a 45-inch seam height significantly increases, compared to a 60-inch seam height, the forward bending moment, twisting moment, compression force, and trunk muscle activity for lateral movements and extending the torso. Impact: Mining industry can use this information to reduce loads on the low back through better work postures from redesigning the machine's workstation and modifying bolting cycle work procedures.

INTRODUCTION

Experts generally accept that the risk of suffering from low back disorders is associated with body posture during lifting activities at the workplace. (Andersson [1991], Kelsey and White [1980], Liira et al. [1996], Phillips and Repperger [2002], Pope [1989]) Low back disorders continue to be the most costly and common musculoskeletal problem facing society today. Back problems are second only to the common cold as the reason that most people visit physicians. During 1997-2001, Mine Health and Safety Administration (MSHA) reported that 32% of back injuries while operating mobile mine equipment occurred to operators of roof bolting machines and was second only to back injuries experienced while mine personnel performed maintenance on equipment (35% of back injuries). Underground coal mine workers often work in reduced vertical workspace where standing upright is not possible and work posturing typically includes kneeling either on one or both knees.

Roof bolting is one of the most basic functions and most dangerous jobs in underground coal mining operations. Roof bolts are the principal method of roof support in mines and are essential to ventilation and safety. After miner crews remove a section of the coal seam, roof bolting machine operators install bolts (steel rods) to secure areas of unsupported roof. A bolter crew's typical work sequence includes tramming and positioning the machine (figure 1), general preparation and

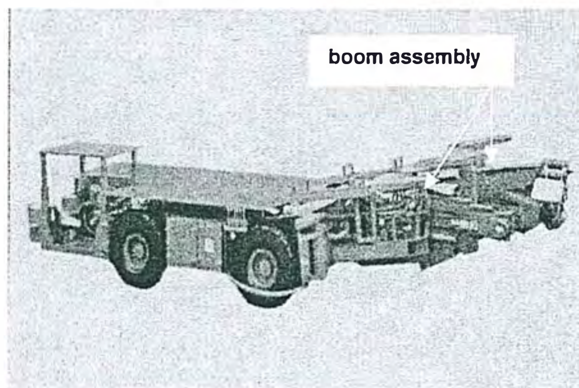

Figure 1. - Roof bolting machine (Courtesy of Fletcher Mining Equipment, Huntington, WV)

setup, drilling a hole and installing a bolt. Drilling bolt holes involves inserting the drill steel in the chuck (adding extension steels if necessary), changing the bits, drilling the hole, and removing the steel. Bolt installation involves making up bolt and washer, inserting resins in the hole if necessary, bending bolts, inserting bolts into the hole, aligning the bolts, raising bolts, and spinning to mix resin or torque the installed bolt. The sequence repeats until the assigned area of the roof is secure and then the machine trams to a new location.

The roof bolter operator does his or her job in a confined environment (for example as shown in figure 2) in a limited working height such as 45-in (inch). This restricted work environment can put the operator in awkward postures for performing or completing his or her tasks.

Incident investigation reports from the MSHA do not contain scientific information to aid in studying musculoskeletal problems associated with underground mine

Figure 2. - Operator in a confined environment

machine operators (Ambrose [2000, 2001]). Field experiments with human subjects (machine operators) are also not feasible because of safety and ethical issues to both the investigators and equipment operators. Therefore, the purpose of this study was to examine the load effects on the low back of underground roof bolter operators by posture and seam height using statistical methods on data collected using digital human simulations

METHOD

SUBJECTS - Ten male and two female subjects experienced in roof bolting operation from the United Mine Workers of America volunteered to perform a series of tasks associated with a roof bolting cycle. Since the objective of the study was not to duplicate the entire mining population, but to represent an accurate picture of the roof bolter population, a sample of 12 human subjects was tested. Table 1 provides information on height, weight, age and gender of the subjects.

EXPERIMENTAL DESIGN - The study evaluated spinal and trunk muscle loads when the subject performs a roof bolting cycle that includes drilling the hole and inserting a roof bolt. Tests were performed that captured and measured human motions by using Ascensions' MotionStar motion-tracking system and recorded by a computer executing the human motion-capture module in Jack simulation software. Researchers asked test subjects to position themselves in a representative bolt insertion positions with respect to a working wooden mock-up of a boom assembly to a roof bolter (Figure 3) and perform roof-bolting procedures as they would on the job. Due to the limitations of use of the MotionStar motion-tracking system around ferrous metals, Bartels et al [2001, 2003] constructed the wooden mock-up from plans provided by J. H. Fletcher & Co.; the boom assembly mock-up was an exact physical reconstruction of the original equipment. The independent variable consisted of seven posture/seam height combinations. Subjects served as a random effect. In this study, researchers manipulated the following lifting postures: kneeling on the right knee, kneeling on the left knee, kneeling on both knees (kneeling postures were used in 45-in, 60-in seams) and standing (only possible in the 72-in seam).

A database containing force and moment values for the L4/L5 spinal joint and trunk muscle forces for ten trunk muscles was prepared by processing the captured motions from each subject using Jack software's *task analysis toolkit – lower back analysis*. The spinal joint load predictions include compression and shear forces: lateral shear force (F_X), AP shear force (F_Y), compression force (F_Z), forward bending moment (M_X), lateral bending moment (M_Y), twisting moment (M_Z). The trunk muscle force predictions were obtained for lateral moves with the right and left erectors (RES, LES), for extending the torso with the right and left latissimus dorsi (RLD, LLD), and for support /flex movement with the right and left external obliques (REO, LEO), the right and left internal oblique (RIO, LIO), and the right and left rectus abdominis (RRA, LRA).

Table 1. – Test subject anthropometric data

subject	height (in)	weight (lbs.)	age (yrs)	sex
human 1	71.0	187.2	47	M
human 2	68.7	135.8	54	M
human 3	69.4	177.7	41	M
human 4	69.2	179.5	44	M
human 5	70.4	185.9	49	M
human 6	71.9	194.0	49	M
human 7	66.5	169.8	53	F
human 8	66.4	168.5	47	F
human 9	69.7	183.9	50	M
human 10	71.8	198.2	47	M
human 11	69.3	183.0	44	M
human 12	68.3	174.9	48	M

Figure 3. - Operator working the wooden mock-up

PROCEDURE AND TASK - Researchers supplied the test subjects with standard mining safety equipment consisting of a hardhat, kneepads and safety glasses. Furthermore, researchers had each subject to position themselves in a specified posture with respect to the working wooden mock-up boom assembly. At a given signal, they completed a roof bolting sequence. The specific roof bolting tasks include: insert drill steel, raise boom to drill a hole, lower boom and remove drill steel, put bolt (using a wrench if needed) in chuck, and raise boom to install bolt, torque bolt and lower the boom and remove wrench. For safety reasons, each object (drill bit, wrench and bolt/plate) the test subject held was made of wood and weighted no more than 1 pound. Test subjects repeated the sequence three times in each posture and in each of the seam heights. Researchers made a video recording of each test session and by using a motion tracking system, measured and recorded the human motions. Subject's test postures in 45- and 60-in seam heights performed with the operator kneeling posture on either the left knee, right knee or both knees. Subject's test posture in an unrestricted 72-in seam height would stand if possible or hunch over to perform the task in the standing posture.

DATA ANALYSIS - Jack's software bases the *task analysis toolkit* on a biomechanical low back model incorporating anatomical and physiological data from scientific literature, most notably Raschke [1994] and Raschke et al. [1996]. In conjunction with the *toolkit*, timed-handloads TATReporter, a Jack module, outputs the forces generated in the *toolkit* to a formatted Microsoft Excel file. Moreover, the TATReporter enables researchers to assign weights to the objects that the subject lifts at specific times during the bolting cycle thus creating realistic loading effects. The assigned object weights were: drill bit, 6 lbs. (pounds); wrench, 4 lbs.; and bolt/plate, 8 lbs. Video recordings of the test session helped to identify the correct times the subject held objects. Researchers obtained a final database by processing the entire set of Excel files (generated by the *toolkit*) with respect to the mean and maximum values of the compression, shear, and trunk muscle force responses from each subject. Researchers acquired from this final database descriptive statistics of force responses by seam and posture and performed an analysis of variance (ANOVA) with a *priori* orthogonal contrasts of the following comparisons: standing vs. kneeling, kneeling in 60-in vs. 45-in seams, kneeling on both knees vs. on one knee, and kneeling on the left knee vs. the right knee. For significant omnibus tests, these contrasts helped elucidate the source of the significant overall F-test. F statistic determines if the differences among a number of sample means are statistically significant.

RESULTS

COMPRESSION, SHEAR AND MOMENT PREDICTIONS - Notable increases in the compression force (F_Z) and forward bending moments (M_X) are reflected in all cases of seam height or work posture (see figures 4, 5, 6, and 7). Compression forces (F_Z) by work posture or seam height exceed shear forces (F_X and F_Y) by 5 to 39 times as much. The same comparison is found of the forward moment (M_X) to the other moments (M_Y and M_Z) by 2 to 8 times as much. Regardless of seam height or work posture, muscle trunk activity in the right or left erectors (RES or LES) accounted for the greater part of muscle activity (see figures 8 and 9) and experienced 3 to 380 times as much force then other muscles.

SOURCE OF VARIATION PREDICTIONS – Tables 1 and 2 summarizes F statistics and contrast for predicting forces and moments acting on the L4/L5 joint and forces on ten trunk muscles. F-test results compared several variations: standing vs. kneeling, kneeling in 60-in vs. 45-in seam heights, both knees posture vs. one knee, and left knee vs. right knee posture.

Effects of Standing vs. Kneeling - The forward bending moment (M_X) significantly increased and twisting moment (M_Z) slightly increased in standing versus kneeling. The compression force (F_Z) significantly increased and AP shear force (F_Y) slightly increased in standing versus kneeling. Neither lateral bending moment (M_Y) nor the lateral force (F_X) were affected ($p>0.05$) when comparing standing to kneeling. The primary spine extensors (RES, LES, RLD, LLD, REO, LEO, RIO and LIO) showed significant activity in standing versus kneeling with the greatest amount of standing activity in RES, LES and LLD. Both RRA and LRA trunk muscles were not affected ($p>0.05$) when comparing standing posture to kneeling postures.

Effects of Kneeling in 60-in vs. 45-in Seam Heights - The forward bending moment (M_X) and the twisting moment (M_Z) significantly increased in the 45-in versus 60-in. The compression (F_Z) and AP shear force (F_Y) significantly increased in the 45-in versus 60-in. Neither the lateral-bending moment (M_Y) nor the lateral shear force (F_X) was affected ($p>0.05$) by seam heights. The primary spine extensors (RES, LES, RLD, and LLD) showed significant activity in 45-in versus 60-in with the greatest amount of 45-in activity in RES and LES. Only LIO had a small increase in activity when kneeling in 60-in versus 45-in. The REO, LEO, RIO, RRA and LRA trunk muscles were not affected ($p>0.05$) when comparing 60-in to 45-in seam heights.

Effects of Kneeling on Both Knees vs. One-Knee - The forward bending moment (M_X) and the twisting moment (M_Z) significantly increased in one-knee versus both knees. The compression force (F_Z) and AP shear force (F_Y) significantly increased and the lateral shear force (F_X) slightly increased in one-knee versus both knees. The primary spine extensors (RES, LES, RLD, and LLD) showed significant activity in the one-knee versus both knees with the greatest amount of one-knee activity in RES and LES. The REO, RRA and LRA showed small increases in activity when on both knees versus one-knee. The LEO, RIO and LIO trunk muscles were not affected ($p>0.05$) when comparing both knees to one-knee.

Effects of the Left Knee vs. the Right Knee - The twisting moment (M_Z) increased slightly in the left knee versus right knee. Neither the forward (M_X) or lateral bending moments (M_Y) nor the compression force (F_Z) were affected ($p>0.05$) when comparing left knee to right knee. Both shear forces (F_X and F_Y) increased slightly in the left knee versus right knee. The spine extensors (RES, RLD, LEO, and RIO) showed significant activity in the left knee versus right knee with the greatest amount of left knee activity in RIO and RLD. The spine extensors (LES, LLD, REO and LIO) showed significant activity in right knee versus left knee with the greatest amount of right knee activity in LIO. Both RRA and LRA trunk muscles were not affected ($p>0.05$) when comparing left knee to right knee.

DISCUSSION

Results of this study indicate that the operator's standing work posture increases the forward bending moment, compression force and any trunk muscle activity more than either kneeling postures. Operator's kneeling postures in a 45-in seam height significantly increases, compared to a 60-in seam height, the forward bending moment, twisting moment, compression force, and trunk muscle activity for lateral movements and extending the torso. The operator's one knee work postures significantly affects more than the both knee posture the forward bending moment, twisting moment, compression, lateral shear and anterior-posterior shear forces, and trunk muscle activity for lateral movements and extending the torso. Operator's left knee and right knee postures both significantly affect muscle activity for extending the torso and support/flexing.

Results of this research have significant implications in terms of evaluating the risk of low back disorders for underground roof bolter operators who must employ restricted work postures and to improve the design of the jobs they must perform and equipment they operate. Researchers plan to use the results and examine further specific recommendations for improving equipment designs and operating procedures in operator's restricted postures through a better understanding of forces and trunk muscle activity and their effects on spinal loading.

Because of the manual work required in hand time load assignments, NIOSH developed a customized program that makes portions of Jack's TATReporter's manual operation easier. NIOSH's program automates and streamlines the process used to generate the **<test name>.timedhload** files required for input to the Jack module. It allows for manual control of the video playback of a test session. As the observed loads in each of the operator's hands change, researchers can add these states to a table recording that information. The program operates on a pre-existing video file, requires setting time synchronization parameters, enables one to step through the video and save each state where a change in hand weighting occurs, and finally, saves directly to a **timedhload** file format needed for input to the Jack module.

CONCLUSION

The outcome of this study illustrates the ease of estimating spinal loads for equipment operators using digital human simulations and associated software modules. Because of posture limitations when using the *toolkit*, the resulting predictions are estimated values. These values are valid for any work posture if the support is below the waist and the weights or forces applied to the virtual human is above the waist such as with hand loads. Three-dimensional computer simulations provide machine designers and safety analysts with a technique for evaluating the workplace. Anthropos, Jack, Ramsis, and Safework are commercial software tools that use digital model humans for ergonomic analyses and work performance evaluations. Authors of the paper strongly suggest the development of *toolkits* that consider loaded forces anywhere and other work postures besides standing such as kneeling, stooping, on the back, on the stomach, on all fours, crawling, etc.

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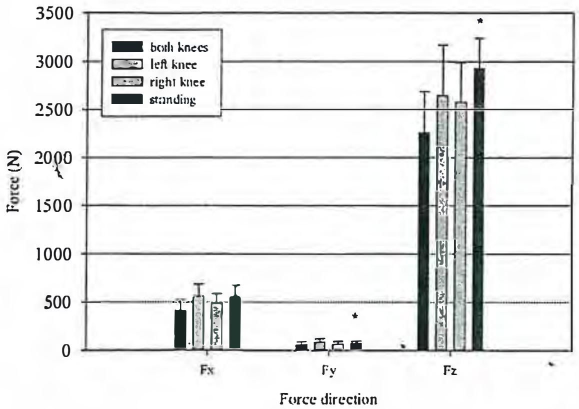

Figure 4. - Mean and standard deviation for compression and shear response by posture

(* identifies significant difference for standing vs. kneeling)

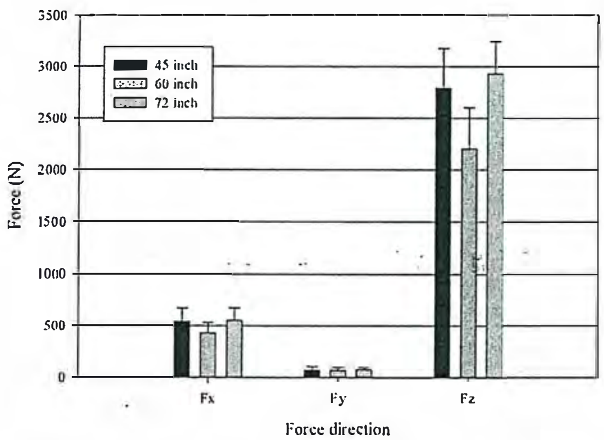

Figure 5. - Mean and standard deviation for compression and shear response by seam height

(* identifies significant difference for kneeling in 60-in vs. 45-in)

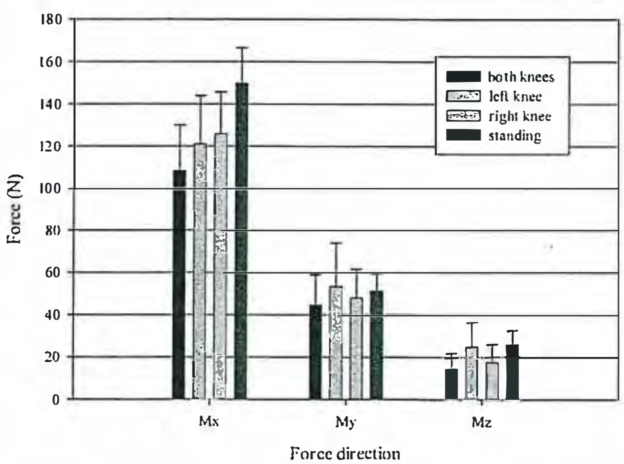

Figure 6. - Mean and standard deviation for moment response by posture

(* identifies significant difference for standing vs. kneeling)

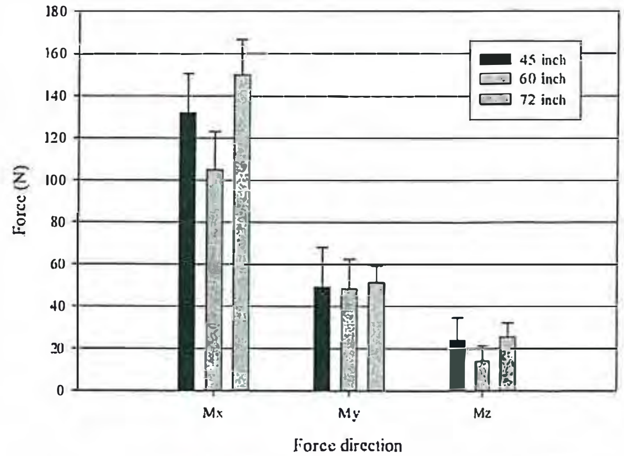

Figure 7. - Mean and standard deviation for moment response by seam height

(* identifies significant difference for kneeling in 60-in vs. 45-in)

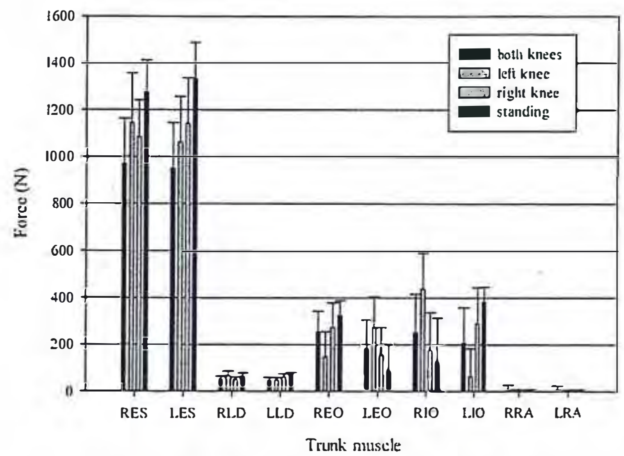

Figure 8. - Mean and standard deviation for trunk muscle response by posture

(* identifies significant difference for standing vs. kneeling)

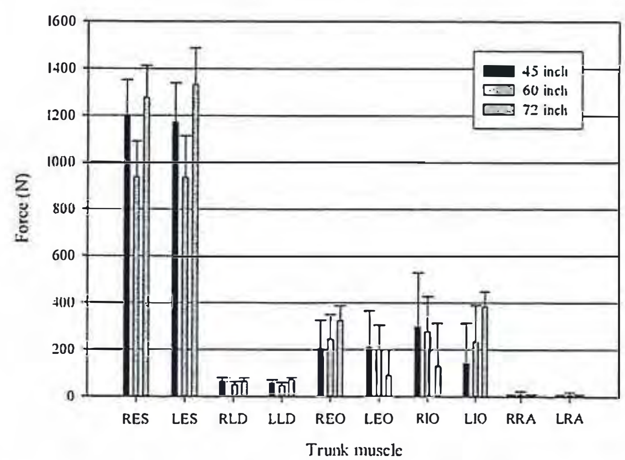

Figure 9. - Mean and standard deviation for muscle trunk response by seam height

(* identifies significant difference for kneeling in 60-in vs. 45-in)

Table 2. – Summary of F statistics and contrast for predicted forces and moments acting on the L4/L5 joint.

Source of variation	df⁺	F_X	F_Y	F_Z	M_X	M_Y	M_Z
Standing vs. Kneeling	234		F-test 2.66* contrast S > K	15.98* S > K	47.34* S > K		4.94* S > K
kneeling in 60 inch vs. 45 inch	234		F-test 17.07* contrast 45 > 60	53.23* 45 > 60	63.24* 45 > 60		21.41* 45 > 60
both knees vs. one knee	234	F-test 3.80* contrast one > both	11.74* one > both	15.89* one > both	17.22* one > both		9.74* one > both
left knee vs. right knee	234	F-test 4.34* contrast left > right	4.44* left > right				7.56* left > right

* = significant at 0.05 ⁺ degrees of freedom

Legend: lateral shear force F_X, AP shear force F_Y, compression force F_Z, forward bending moment M_X, lateral bending moment M_Y, twisting moment M_Z

Table 3. – Summary of F statistics and contrast for predicted forces on ten trunk muscles.

source of variation	df⁺	RES	LES	RLD	LLD	REO	LEO	RIO	LIO	RRA	LRA
Standing vs. Kneeling	234	F-test 25.87* contrast S > K	44.56* S > K	3.09* S > K	35.65* S > K	8.01* S > K	13.68* S > K	11.17* S > K	17.80* S > K		
kneeling in 60 inch vs. 45 inch	234	F-test 76.01* contrast 45 > 60	56.85* 45 > 60	23.21* 45 > 60	23.63* 45 > 60				5.59* 60 > 45		
both knees vs. one knee	234	F-test 18.97* contrast one > both	19.27* one > both	6.60* one > both	7.78* one > both	2.53* both > one				2.27* both > one	2.91* both > one
left knee vs. right knee	234	F-test 2.85* contrast left > right	4.30* right > left	21.21* left > right	18.09* right > left	15.20* right > left	15.10* left > right	31.50* left > right	28.99* right > left		

* = significant at 0.05 ⁺ degrees of freedom

Legend: lateral moves with the right and left erectors (RES, LES), for extending the torso with the right and left latissimus dorsi (RLD, LLD), and for support /flex movement with the right and left external obliques (REO, LEO), the right and left internal oblique (RIO, LIO), and the right and left rectus abdominis (RRA, LRA)