Verification and Validation of Roof Bolter Simulation Models for Studying Events Between a Machine and its Operator

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ABSTRACT

This paper presents the results of a study to verify and validate a computer model that represents and analyzes motions and hazardous events in a simulated three-dimensional workplace. The purpose of the computer model is to support research that is investigating the safe speed range for the vertical movement of roof bolter boom arms to reduce worker injuries in underground coal mines. The information obtained for this paper is based upon a project that is investigating means to reduce workers risks of injury from exposure to mining machinery. The methodology being employed by the project includes human factors design considerations, anthropometric modeling and simulation tools, laboratory validation, engineering interventions, and collaboration with industry and an equipment manufacturer. The results of this study were used to (1) determine the input parameters that are unique to the mining environment and needed to develop a credible, computer-based, human-machine interactive model, (2) develop test methods to measure the required parameters, and (3) to refine the human-machine interactive computer model.

INTRODUCTION

PROBLEM

There is currently no regulations or method of determining the safe speed of roof bolter boom arms. Three dimensional computer simulations provide machine designers and safety analysts with an accurate model for evaluating collision hazards concerning operator-machine interaction. Computer simulations of roof bolting tasks were conducted using bolter machine and bio-mechanical human models that ran on Unigraphics Solutions /Engineering Animation Inc's JACK simulation software. Computer simulation allows multiple environments, virtual humans, and differing scenarios to be studied, which would be dangerous and time- and cost-prohibitive with field data studies. Before collecting final data, preliminary results of the roof bolter model need to be validated to ensure that parameter assumptions made for the computer-based simulation conform to actual field practice. This study verified operators' response times, task motions, and field of view relative to the roof bolter boom arm. Human subjects tests with a full scale working mockup of a roof bolter boom arm were used for collecting motion data that helped determine parameters for building valid and credible models.

BACKGROUND

After miner crews in underground coal mines have cut a section of coal, roof bolter operators have the job of installing steel rods (bolts) into the mine roof to control cave-ins by securing sections of unsupported roof. Roof bolting may be regarded as a fairly structured and repetitive work situation. The entire bolting operation must be completed in a confined environment, for example, limited working height as low as 114.3-cm (45-in), in the vicinity of moving machinery (Figure 1). The problem becomes more pronounced the lower the seam height becomes. The confined environment requires the operator to work in awkward postures and to perform tasks requiring fast reaction times to avoid being hit by the moving machine appendages. Further compounding the problem is the low lighting conditions found in mines and the restricted visibility due to the protective canopy on the bolter machine. These conditions combine to make roof bolting one of the most dangerous occupations in underground mining. For the years 1992 through 1996, the Mine Safety and Health Administration (MSHA) injury database showed there was an average of 961 roof bolter operator accidents per year, representing 16% of all equipment related accidents, in underground coal mines.

In order to address safety issues, a roof-bolter-machine committee was established by MSHA in 1994. The members of the committee were composed of MSHA, the West Virginia Board of Coal Mine Health and Safety, NIOSH, and roof bolter manufacturers. This committee studied 613 accidents that occurred during drilling and roof-bolt installation. The committee also looked at 15 fatalities attributed to inadvertent or incorrect actuation of the feed control lever, while the operator was within the drill head or boom arm pinch-point area. One outcome of this committee's study was the realization that there was no data on the safe speeds for roof bolter booms operating close to workers in a confined environment like an underground coal mine. Emphasis was placed on hazards related to the movement of the boom arm or mast of a roof-bolting machine. The committee's objective was to identify hazards and recommend solutions. The data-collection effort consisted of analysis of: MSHA accident data; visits to underground mines and interviews with experienced roof bolting machine operators; discussions with roof bolting machine manufacturers; interviews with workers injured while performing roof bolting tasks; and reviews of research on roof bolting safety. A set of recommendations to increase the safety of roof bolting operations was developed, in particular, reduction of the bolter boom arm speed.

The main question that needs to be answered is what range of boom speeds minimizes the roof bolter operators' chances of injury while still allowing the roof bolter operator to perform his job effectively. This question becomes even more important in light of potential rules proposed by MSHA on improving the design of roof bolters.

The information needed to answer this question is: 1) When does the operator see the boom arm and drill head during the roof bolting operation? 2) How frequently are there collisions between the operator and the roof bolter machine appendages? 3) What are the distances between the operator's hands, arms, legs and head and the roof bolter's boom arm and drill head during each of the bolter operator's job tasks? 4) What changes do various operator postures, such as kneeling on one knee or two knees, make in these other parameters?

In order to effectively answer these questions, a sufficient number of studies must be conducted to collect collision data that covers all of the variables. Laboratory and field experiments examining these situations are difficult because of the complexity and the instantaneous nature of the occurrences. Therefore, a computer-based, three dimensional solid object approach is being used as the primary means to generate and collect the data. Data collected in the roof bolter model consisted of the counting of mishaps. In the model, a mishap means two or more objects intersecting; for example, the boom arm collides with the operator's arm, hand or leg. Hazardous conditions were collected in three-dimensional computer environments using collision detection. Consequently, limited laboratory experiments were needed to provide accurate parameters for the roof bolter model, and to validate the computer simulations.

The roof bolting operation was broken down into specific tasks. Klishis et al observed the tasks and the amount of time spent on each task. [5] The task list provided a guide in developing the experimental design for laboratory human subject tests and discrete movement scenarios for the computer simulations. This computer-based simulation was used to generate and collect collision data between the machine and it's operator while recording many variables, such as the operator's response times, operator postures, risk behaviors, anthropometry, and machine appendage velocity. The roof bolter model evolved from code developed in Lisp and Jack-Command-Language that creates random human motions, random motion goals for the hands and torso, and random motion of events reflecting operator's behavior.

The uncertainty or variability inherent in operator movement required for the drilling and bolting tasks was incorporated into the model to effectively determine the likelihood of an operator being injured. In the model random motion is generated, individual paths differed slightly even though the motions look very similar. The model incorporates variability in the motion and a path variance within that motion. Thus, for a machine and operator, the operator's various risk behaviors, motions for each risk behavior, and motion paths associated with each motion behavior, and moving machine appendages have some degree of variability. These random motions give the model a realistic representation of the operator's motions and behaviors found during the control of any roof bolter task. A model that includes any random aspects must involve sampling, or generating random variants. The phrase "generating a random variant" means to observe or realize a random variable from some desired arrangement of values of variables showing their observed or theoretical frequency of occurrence. To determine the range of these differences, laboratory motion tests were conducted using experienced roof bolter operators.

RESEARCH QUESTIONS ADDRESSED

1. Does the reduced lighting conditions in underground coal mines reduce the optimum viewing area of a worker? Federal regulation requires illumination levels around a roof-bolting machine to be 0.06 fl (foot-Lambert). It is unknown if these lighting conditions will affect the area in which an individual can detect a moving hazard. Optimum viewing areas in which roof bolt operators can detect moving hazards were measured, using standard optometrists' equipment, under normal lighting conditions and under mine illumination conditions

2. What is the whole body response time of an individual performing bolting tasks in various postures and various mine seam heights ranging from 114.3-cm (45-in) to 182.9-cm (72-in)? Due to the confined environment of mining, the postures of bolter operators are unlike the postures of workers in other occupations. What effect does restricted space have on individual response times required to perceive and avoid hazards? When equipment operators detect a machine hazard, they want to get out of the way. In spite of awkward positions and postures imposed on operators by their confined environment, they require quick responses to dangerous situations. To assist in the response time investigation, operator motion was recorded, while they avoided the moving appendages of the roof bolting machine.

3. How well does the computer simulation of roof bolter tasks match the actual movements of individuals (what is the motion envelope for each of the bolting tasks)?

4. What is the operator's position and orientation with respect to the bolter's controls and boom arm appendage? The starting position of the operator defines the movement envelope generated by the computer simulation for the virtual humans.

STUDY POPULATION

The study population for the computer simulation covers the 5th through 95th percentile male. The study population represents the target population, which is 99% male, however two female miners were among the study volunteers and were used to represent the 20th to 30th percentile male operators due to the rarity of female operators. Since the objective of the laboratory tests is not to duplicate the entire simulation population, but only to verify that the simulation represents an accurate picture of the real world, a small sample of 12 subjects were tested. Movements of the virtual human will be compared to those of their test subject counterpart to evaluate the performance of the model. The optimum viewing area tests used 12 local subjects from NIOSH's Pittsburgh Research Laboratory (PRL) since no special mining skill was involved. The response time and human motion data testing were conducted using 12 subjects from the local office of the United Mine Workers of America (UMWA), which included two female volunteers which were included in the study, to accurately duplicate the skills and experience involved in operating mining equipment. The anthropometrics for the 12 subjects used in motion and response time studies are listed in Table 1.

DATA COLLECTION

Laboratory tests were performed on human subjects and the results were used to compare laboratory and computer simulation results for basic input parameters to the roof bolter model (Figure 2). Also, the optimal viewing area (vision cone) and human motion data were used to evaluate the accuracy of the computer simulation. Operators' response times were used to quantify the effects of parameter values that are used with the computer simulation to determine occurrences of collision and collision avoidance.

FIELD Of VISION IN REDUCED LIGHTING

For acceptable viewing in reduced lighting conditions, MSHA minimum lighting requirements mandates illumination levels of 0.06 fl. Testing was required to determine the viewing area, accurate field of vision and awareness of hazards with this background lighting and a cap lamp. Measurements were made using standard optometrists' peripheral vision measuring equipment. Visual acuity was tested using Snellen charts. If subjects normally used glasses or contact lenses to correct their vision, the subject wore these items during the vision tests. Dependent measures included tests of peripheral vision (using a modified Peripheral Vision Chart), and visual acuity (using Snellen eye charts).

Five tests were performed with each subject for both the visual acuity and field of visions. Using normal procedures for visual acuity testing, the subject was seated 609.6-cm (240-in) away from the Snellen charts and a standardized procedure was used to determine the smallest row of letters that the subject could read under the experimental conditions.

The five vision test conditions consist of a normal lighting level, a 0.06 fl level, 0.06 fl levels with a cap lamp, 0.03 fl level, and 0.03 fl levels with a cap lamp. Test subjects were asked to wear a standard hard hat and, for two tests, a hardhat and cap lamp. The test subjects were placed in a seated position. The background lighting was adjusted to normal, 0.06 fl, 0.06 fl wearing a cap lamp, 0.03 fl and 0.03 fl wearing a cap lamp. The subjects were asked to place their head against a rest 60.96-cm (24-in) from a modified peripheral vision chart. Test subjects were instructed to indicate when they detected the movement of a white ball under each of the three different lighting conditions. Tests were conducted at 45 degree increments above and below the horizontal plane (on both sides) and vertically from directly above the head. The angle at which the subject becomes aware of the white ball in their field of vision was recorded for each experimental condition.

HUMAN RESPONSE IN ROOF BOLTING POSTURES

Human motion response times were measured for the operator postures unique to operating a roof bolter. Appendix A describes the equipment constructed and used for this human subjects testing. Operator test postures in 114.3-cm (45-in) and 152.4-cm (60-in) seam heights were performed with the operator kneeling, leaning forward with the head tilted to one side and looking at a drilled hole location. The operator's test posture in a 182.9-cm (72-in) seam height would be to stand if possible or hunch over to accommodate the standing posture. The tests trials were repeated three times for each seam height and in the following postures: kneeling on one knee at a time and kneeling on both knees. The tests were repeated for 182.9-cm seams in a standing or stooping posture. The human motions were measured and recorded using the motion tracking system. Appendix B describes the motion tracking system used in the laboratory tests.

Test subjects were asked to position themselves in a bolt insertion position with respect to the wooden mockup roof bolter. The right hand was situated on the bolter controls and the left hand on the drill steel. The head was above the boom, and the subject looked at the drill hole. At a given verbal signal, the test subjects were instructed to move themselves from the motion envelope of the bolter boom (move from a forward leaning position with extended arms to a vertical position with arms resting at the side). The timing of the verbal cue was random so that the subject was not able to anticipate when to start moving. For each experimental condition, three repetitions of the test were performed. At least two minutes of rest was provided between repetitions. This information was used to determine if the simulated human could have avoided a collision with the bolter boom.

HUMAN MOTION ENVELOPS

The human motion envelopes were measured for the operator postures unique when operating the roof bolter. Operator test postures in 114.3-cm (45-in) and 152.4 (60-in) seam heights were performed with the operator kneeling posture either on one or two knees. Operator's test posture in 182.9-cm (72-in) seam height would stand if possible or hunch over to accommodate the standing posture. The subjects were supplied with standard mining safety equipment consisting of a hardhat, kneepads and safety glasses. The human motion envelopes were measured and recorded using a motion tracking system.

Test subjects were asked to position themselves in a specified posture with respect to the working wooden mockup roof bolter. At a given signal they completed a roof bolting sequence. The specific roof bolting tasks were: insert drill steel, raise boom to drill 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. Typically a complete bolting sequence can be completed in 25 to 30 seconds. The sequence was repeated three times in each posture in each of the seam heights

DATA ANALYSIS

A randomized block experimental design was utilized for all phases of the study. Dependent measures in this experiment were analyzed using an Analysis of Variance (ANOVA), using a significance level of 95%, to determine whether significant differences existed between the experimental conditions. If the ANOVA indicated that a significant difference existed, the Neuman-Keuls multiple range test was used to identify those conditions where significant differences existed.

FIELD OF VISION IN REDUCED LIGHTING

The results of analysis were averaged for the 12 subjects and a vision area for the unique lighting conditions of underground mining environments was developed, which accounted for the use of a cap lamp and the reduction of viewing area by the use of a standard hard hat. The results of the tests in 0.06fL lighting with a miner's cap lamp and hard hat were the most significant in terms of input to the simulation model. Typical results are shown in Table 2 and Figure 3.

The most significant reduction in a subject's vision cone appeared to be a result of the reduction of the viewing area caused by the hard hat. The rods of the eye, which become more active in low light and allow night vision, were also the most sensitive to movement in the cone of vision. The response of the eye rods was only slightly diminished.

HUMAN RESPONSE IN ROOF BOLTING POSTURES

Human response time is categorized by three discrete events: (1) The recognition of the initialization signal; (2) the cognitive interpretation of the signal; and (3) the actual reaction. Since events 1 and 2 are well documented, our main concern was the response in the confined and limiting mine environment, which had not been previously studied. Three trials were captured with the motion tracking system. The operator reaction times were then averaged for each test subject. Summery results were obtained from Figure 4.

The data for the head and hands were considered the most significant for reaction characterization because these are the body parts most likely to be injured. Engineering parameters were calculated for these sensors. Table 3 shows a sample of typical results. Average and maximum velocity and acceleration were calculated for each of the sensors.

The range of variation is what one might expect from human motion, maximum speed and acceleration increase as the working space increased. When the data is viewed as a function of scale, the variations in reaction parameters were reasonable. This range was averaged by anthropometrical size, based on the National Health Examination Survey [9], and used as the reaction response for the digital human model. The reaction time of operators is significant when determining if an operator will be able to avoid a moving object posing a hazard.

HUMAN MOTION ENVELOPES

In order to provide input parameters to the virtual human simulation, the data from the motion tracking and capturing system was divided into six discrete tasks: (1) loading the drill steel into the bolter arm; (2) drilling the roof; (3) lowering the bolter arm; (4) loading the roof bolt into the bolter arm; (5) bolting the roof; and (6) lowering the bolter arm. The discrete points in the data where these particular events occurred were identified by the start and stop points of a motion sensor mounted on the drill boom). To identify these points, a graph of the acceleration of this sensor was overlaid on the graph of the boom movement. The points of maximum acceleration mark the start and stop points of the boom (Figure 5).

The motion data for each of the three trials by a single test subject were then analyzed using ANOVA. For tasks 2, 3, 5 and 6, the position of the moving boom was used as the independent variable and the change in a scalar vector from the boom sensor to the body point sensor being studied was used as the independent variable. Standard deviations at each centimeter of bolter boom movement were determined and the maximum standard deviation was selected as the seed number for range of variability for the virtual human movement.

The data for tasks 1and 4 did not lend themselves to this method of statistical analysis due the lack of a consistent independent variable. These data were analyzed by taking a standard deviation of the whole series of data points consisting of a scalar vector from the stationary boom sensor. Since the data for these tasks is not critical for the objective of the study (operator collisions with a moving bolter arm), this was considered adequate. This data was then classified by anthropometrical size for incorporation into the model. Typical results summarized by anthropometrical size, seam height, and operator postures are shown in a small example Table 4.

The results of motion variance analysis produced a scattered range of variation, which at first glance does not produce a consistent pattern. This range of variation was small, when the data is viewed as a function of scale, the variation in movement was reasonable for a repetitive task in a confined environment. The variation in motion also tended to increase as seam height increased providing increased working space. The difference in movement between tests ranged from 2 cm to 30 cm. This range is the seed number, which is close to the originally assumed variance of motion used in the computer-based human model studies.

HUMAN-MACHINE INITIAL START POSTURE

Using the HUMAN MOTION ENVELOP data, an average starting position for the subject's knees and back sensor was determined and a standard deviation for these points determined. The results were then categorized by the subject's height position along the anthropometrical scale and averages obtained for 10 percentile increments. Typical results are shown in Table 5.

Measurement locations of the back and knees provided initial postures of the operator's body relative to the machine. A value of 'angle back Y', i.e. 17.77, provides the angle at which the body is to the boom arm. The 'back X' value, -89.94-cm, provides a distance in the coordinate X direction from the boom arm. This information provides the digital human model with a realistic starting position for the simulated bolting sequence and a valid range of variation in initial position for multiple simulation runs

CONCLUSION

Equipment manufacturers require specific engineering data to provide ergonomically correct designs for worker protection. Digital simulations provide a virtual operator with no limitations; the required tasks can be performed repeatedly in infinite test scenarios. This allows the design parameters to be evaluated with out the need for extensive and potentially dangerous field studies. However, to provide valid models, adequate data defining the human movement and variation of movement are required. This paper shows the methods used to provide that input in to the unique environment of underground mining. The techniques used are also applicable to a range of industrial applications. The model will still need to be verified once the parameters have been incorporated and the results compared to field and lab studies. The data obtained in these human subject tests is also a database that will be used in the eventual validation of the final digital model.

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APPENDIX A - MOCKUP ROOF BOLTER

A model of a typical roof bolter arm was constructed from wood, Figure 6. In all other respects, this model resembled the actual equipment used underground. It was dimensionally identical and moved in the same manner. The use of wood for the construction material was dictated by the requirement for the Flock of Birds motion tracking system, which is sensitive to ferrous metals. The only metal parts in the model were some small pins and shafts at the articulating joints and the hydraulic cylinders.

The wooden bolter boom arm mockup has four hydraulic actuators; one each for boom rise, swing, sump and stabilizer jack. Normally, these actuators are pinned, or otherwise connected, at each end to transmit generated forces to the structure. High pressure 175.75 kgf/cm^2 (2,500 psi) was required in the hydraulic system in order to provide the necessary flow and speed control. Although the actuators were of small diameter, they still were capable of generating high forces due to this pressure requirement. It was not feasible to monitor a pressure rise resulting from an inadvertent contact between the test subject and the mockup. Such a contact would have resulted in a practically undetectable pressure change even though forces high enough to cause injury would be present. There fore a mechanical means to limit the forces available from the mockup was devised. The hydraulic actuators on the bolter arm were all assembled using a slip clutch connector, which limits the amount of force that the actuator can produce. These were adjusted and tested prior to any human subjects testing to insure that they would perform as intended. If contact between the human subject and the moving bolter mockup should occur, the clutch slides on the hydraulic actuator and prevents any injury. These slip clutches were installed on all of the hydraulic actuators in the mockup.

The perimeter of the boom arm mockup was protected from contact with the test subjects with a series of five pairs of class 2 laser emitter diodes and sensors. This system of sensors was connected to a fast dump hydraulic valve. Note that using the sensors to shut off the hydraulic pump would have been ineffective because the pump would continue to produce flow until the motor had coasted to a stop; this would have taken several seconds. The use of a fast acting hydraulic dump valve provided nearly instantaneous halt of the mockup’s motion. In the event of an operator coming close to the moving parts of the bolter mockup, the light curtain would be broken. This would cause the dump valve to open and remove all hydraulic pressure, effectively stopping all movement of the mockup. The electronic interface between the laser sensors and the dump valve was designed to “latch” a break in the sensors light beam. Thus, motion of the bolter mockup would not start again just because the light beam became unobstructed. Once any of the sensors had been tripped, a reset switch had to be depressed to reactivate the system hydraulics. The electronics interface had an indicator display that showed which of the sensors had been tripped. These safety features also were tested extensively to insure the utmost in the human subject’s safety.

The final mechanical precaution was to construct the simulated mine roof from suspended Styrofoam in the unlikely event that the test subject should contact or be trapped between the moving bolter arm and the simulated roof. The lightweight Styrofoam would move out of the way.

In order to assure safe operating speeds, the boom arm speed was limited to 55.88-cm/s (22-in/s) the maximum speed that the roof bolter computer model is set. Normal bolter boom arm speeds can vary (i.e., 17.28- to 55.88-cm/s) depending on the size of the machines hydraulic pump. The hydraulic system for this mockup was designed with flow adjustments on all actuators. These flow controls allowed each of the mockup’s actuator speeds to be controlled independently. The test speed was set for 40.64 cm/s (16-in/s), the speed MSHA is considering as a regulated safe speed.

APPENDIX B - MOTION TRACKING AND DATA CAPTURING SYSTEM

The structure of the UniGraphics Solutions-Engineering Animation Inc., JACK software makes it ideal for use with virtual reality (VR) input and output devices. The use of VR enables the user to become the virtual human figure and inhabit the virtual environment. VR features could become very useful to build valid and credible simulation models. This is possible with the use of VR interfaces that supports sensors, such as using Ascension Flock of Birds with JACK software.

One of the best ways to model human movement is to use a real human to generate motion. The Flock of Birds (FOB) motion tracking system and JACK human modeling software provides these capabilities. Realistic human movements can be recreated in real time using position and orientation information from the Flock of Birds to drive the virtual human figure in a JACK simulation environment. Using FOB’s sensor information, Jack’s MoCap module enables automatic anthropometrical scaling and storage of subjects and the collection and recording of the subject’s motions.

The FOB is a six degree-of-freedom measuring device that can be configured to track the position and orientation of up to 60 sensors by the transmitter simultaneously. Each sensor can make from 30 to 144 measurements per second of its position and orientation when the sensor is found within 10 feet of its transmitter. Ascension provided PRL with a range of frequencies that would optimize a sensor's sensitivity when tracking motion around metallic objects. Tests were run on the bolter mockup around those areas containing metallic objects. PRL's investigators optimized the sensor sensitivity for the test conditions by setting them to 68.3 measurements per second. The FOB determines position and orientation by transmitting a pulse DC magnetic field that is simultaneously measured by all sensors in the Flock. From the measured magnetic field characteristics, each sensor independently computes its position and orientation and makes this information available to a host computer. A FOB setup consisting of more than four sensors are configured into a Motion Star model.

The Motion Star model could consist of a chassis of up to 20 FOB sensors. PRL's Motion Star system currently has only 12 sensors. It takes a minimum of eleven sensors to track the motion of a human adequately and the twelfth defined the roof bolter boom arm (see Table 6). Fasteners used by industry attach the sensor to each wrist, elbow, knee, and foot, and to the neck, head and lower back (see figure 7). Because each sensor has its own independent computer, the measurement rate is independent of the number of sensors. The Ethernet interface was used for FOB's communication with a host computer that ran JACK's software module MoCap.

Table 1. Anthropometrics size of subjects

Subject	Height, cm	Weight, kg	Age	Gender	Percentile	Range
1	180.3	84.9	47	m	83.4	80-90
2	174.5	81.6	54	m	50.1	50-60
3	176.4	80.6	41	m	60.04	60-70
4	175.8	81.4	44	m	57.89	50-60
5	178.9	84.3	49	m	78.07	70-80
6	182.7	88	49	m	91.25	90-95
7	168.9	77	53	f	24.65①	20-30
8	168.7	76.4	47	f	24.30①	20-30
9	176.9	83.4	50	m	62.69	60-70
10	182.4	89.9	47	m	90.13	90-95
11	176.1	83	44	m	58.9	50-60
12	173.4	79.3	48	m	48.91	40-50

①Male percentile used to categorize female subjects
Based on National Health Examination Survey[9]

Table 2. Vision cone in reduced lighting

BOTH EYES					
DEGREES	Normal light 21fL	.06fL	.06fL w/lamp/hat	.03fL	.03fL w/lamp/hat
0	70.02	63.55	65.43	65.84	68.20
45	61.04	63.07	58.06	55.94	55.94
315	65.94	65.01	67.17	62.95	66.04
90	54.28	53.13	34.51	46.17	32.01
270	61.39	57.03	57.38	50.39	59.04
180	60.45	61.93	63.55	61.39	65.22
135	60.83	59.81	64.36	53.56	52.25
225	65.94	65.01	67.17	60.26	64.80
LEFT EYE					
DEGREES	Normal light 21fL	.06fL	.06fL w/lamp/hat	.03fL	.03fL w/lamp/hat
0	53.97	57.03	56.31	49.90	59.66
45	53.56	45.00	36.87	47.29	38.37
315	39.45	52.25	52.70	51.34	55.56
90	43.47	35.71	28.44	38.37	28.44
270	61.39	56.67	56.31	50.39	57.03
180	67.86	62.70	64.25	61.39	62.45
135	54.38	49.90	52.25	49.40	51.34
225	65.64	62.95	62.45	57.72	66.04
RIGHT EYE					
DEGREES	Normal light 21fL	.06fL	.06fL w/lamp/hat	.03fL	.03fL w/lamp/hat
0	66.80	64.25	64.47	60.83	61.39
45	59.19	60.26	61.25	53.97	52.25
315	67.43	64.36	66.04	62.95	68.20
90	42.51	48.63	35.31	40.16	30.26
270	59.66	52.91	59.04	48.37	59.35
180	49.40	48.37	51.34	47.83	56.13
135	51.34	54.78	42.51	48.37	39.81
225	65.74	62.95	62.45	57.72	66.04

Table 3. Example of operator reaction parameters in a 114.3-cm (45-in) seam height

Subject	Position	Maximum Speed of Head, cm/sec	Elapsed Time, sec (*)		Maximum Acceleration, cm/sec^2			Average Speed, cm/sec	
				Head	Left Hand	Right Hand	Head	Left Hand	Right Hand
6	Both Knees	39.18	0.667	392.91	973.04	120.88	26.91	37.61	4.25
	Left Knee	23.19	0.411	332.70	493.99	626.46	16.40	21.02	22.70
	Right Knee	32.76	0.667	394.30	679.48	72.98	24.42	16.84	2.53
10	Both Knees	60.67	0.622	749.18	2978.87	272.38	33.34	53.47	13.04
	Left Knee	97.90	0.733	1438.55	2029.96	533.81	49.61	69.82	17.28
	Right Knee	101.75	0.944	1796.46	1678.98	1609.13	54.10	31.36	24.03
(*) Time to Reach Maximum Speed of Head									

Table 4. Standard deviation of motion 50th - 60th percentile in a 114.3-cm (45-in) seam height

	TASK NO	Std Dev HEAD (cm)	Std Dev LEFT HAND (cm)	Std Dev RIGHT HAND (cm)
Both Knees	1 Insert Drill	5.57	12.27	13.44
	2 Drill Roof	3.68	9.20	2.59
	3 Lower Boom	2.93	16.02	2.87
	4 Insert Bolt	4.49	13.54	21.38
	5 Bolt Roof	2.09	5.12	3.29
	6 Lower Boom	2.56	8.43	5.59
Left Knee	1 Insert Drill	6.03	12.05	17.04
	2 Drill Roof	3.48	13.91	12.64
	3 Lower Boom	3.22	8.45	13.52
	4 Insert Bolt	5.67	12.74	23.93
	5 Bolt Roof	3.83	15.51	11.16
	6 Lower Boom	4.23	3.98	10.53
Right Knee	1 Insert Drill	5.40	6.49	6.18
	2 Drill Roof	4.09	7.15	28.06
	3 Lower Boom	6.11	18.52	14.84
	4 Insert Bolt	8.23	11.28	16.12
	5 Bolt Roof	3.22	6.50	3.77
	6 Lower Boom	4.71	6.44	3.27

Table 5. Starting position for 114.3-cm (45-in) seam height on both knees for 50th-60th percentile

	Mean (cm)	Standard Deviation (cm)
Distance Back	93.08	7.06
Distance Neck	81.11	17.53
Distance Left Knee	48.06	17.22
Distance Right Knee	60.77	14.22
BACK X	-89.94	2.24
BACK Y	60.14	9.18
BACK Z	240.54	2.28
Angle Back X	-94.47	2.87
Angle Back Y	17.77	6.04
Angle Back Z	97.72	5.45
NECK X	-52.94	4.78
NECK Y	97.01	10.07
NECK Z	238.28	5.71
Angel Neck X	-99.41	17.19
Angel Neck Y	63.84	5.39
Angel Neck Z	106.17	23.91
Left Knee X	-48.20	2.31
Left Knee Y	26.43	7.25
Left Knee Z	215.63	3.61
Angel Left Knee X	99.66	3.43
Angel Left Knee Y	30.07	5.27
Angel Left Knee Z	-100.58	13.31
Right Knee X	-42.17	2.83
Right Knee Y	25.64	7.35
Right Knee Z	247.56	3.53
Angel Left Knee X	86.84	5.84
Angel Left Knee Y	28.27	2.62
Angel Left Knee Z	-104.78	3.58

Table 6 – Sensor locations

Sensor	Location
1	Head
2	Waist
3	Neck
4	Left Elbow
5	Right Elbow
6	Left Wrist
7	Right Wrist
8	Left Knee
9	Right Knee
10	Left Foot
11	Right Foot
12	Boom Arm

Figure 1 Roof Bolter Operator in Low Seam

Figure 2. Vision cone in the roof bolter model

Figure 3. Vision cone in degrees

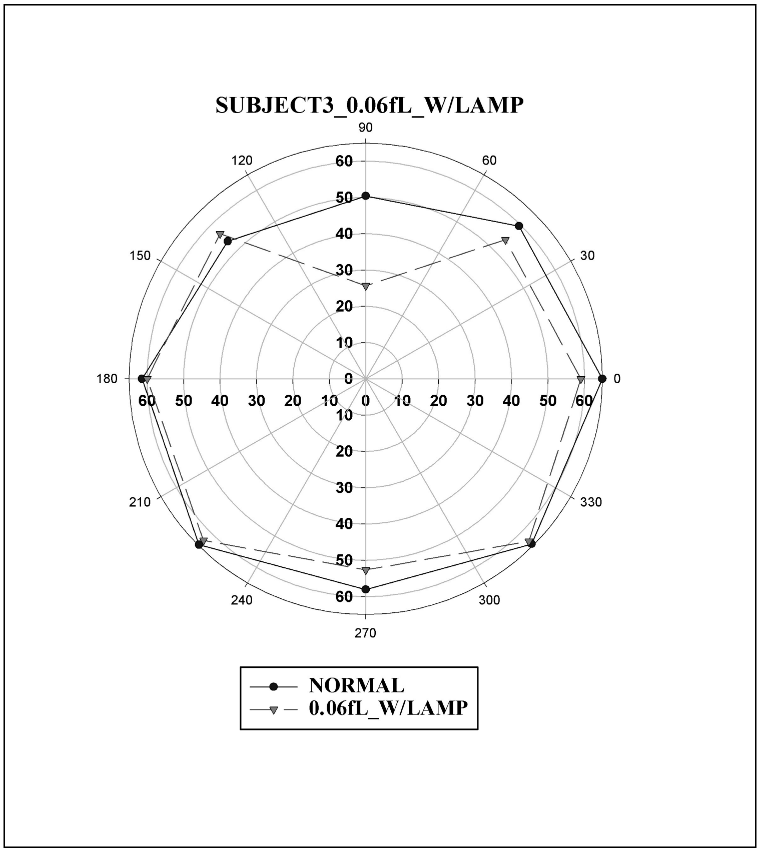

Figure 4. Head reaction in three trials

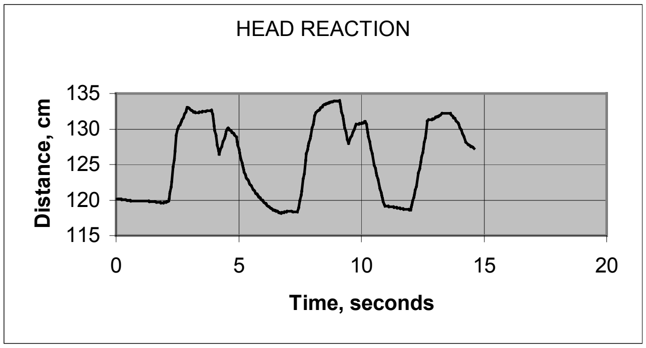

Figure 5. Determination of task starting points

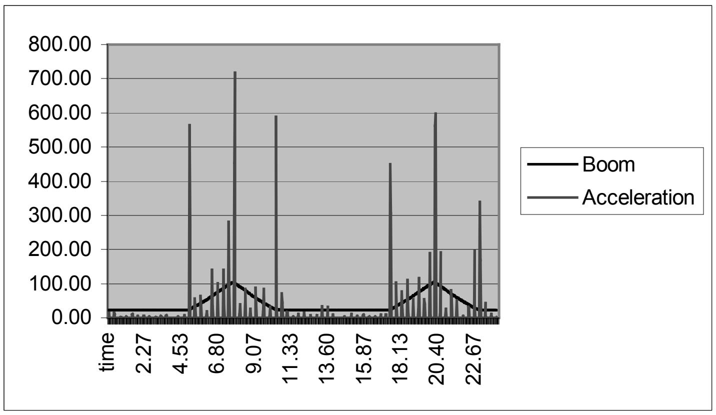

Figure 6. Roof bolter boom arm mockup

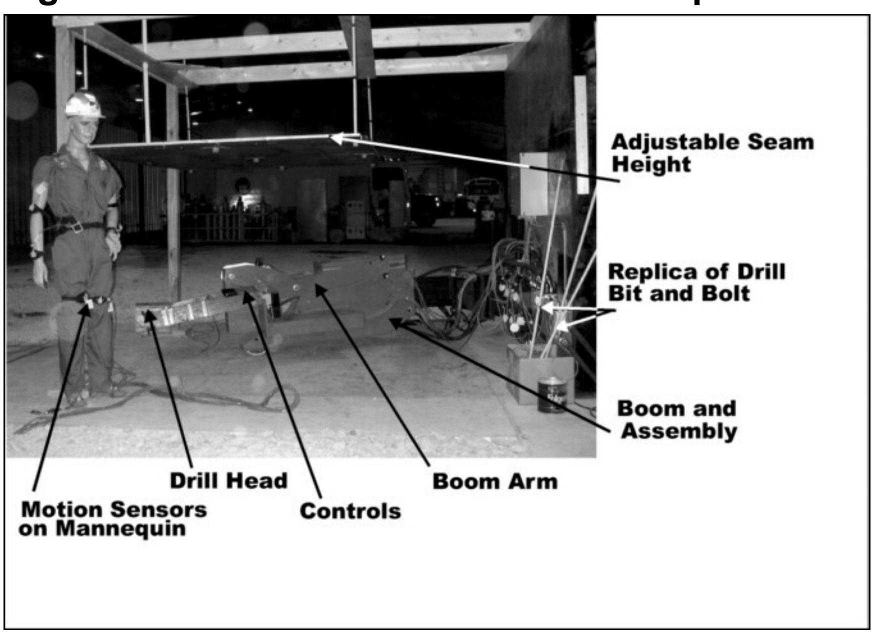

Figure 7. Sensor locations on subject