Computer simulations help determine safe vertical boom speeds for roof bolting in underground coal mines

Dean H. Ambrose , John R. Bartels, August J. Kwitowski,
Sean Gallagher, Thomas R. Battenhouse Jr.

National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory, Pittsburgh, PA 15236, United States

Abstract

Problem: Incident investigation reports do not usually contain enough information to aid in studying boom arm vertical speed for roof bolting machines to determine the impact that appendage speed had on an operator's risk of experiencing a contact. Laboratory experiments with human subjects are also not feasible because of safety and ethical issues. *Method:* Researchers successfully developed a three-dimensional computer model that uses virtual human simulation software as the primary means to gather contact data when the boom arm touches the operator's hand, arm, head, or leg. *Results:* Data analysis of roof bolter simulations shows that the speed of the boom arm is the most important factor in determining the risk of an operator making contact. Regardless of other variables, contact incidents were always greater when the bolter arm was moving up, greater on the hand, and greater for the boom arm part of the machine. The reason why the subject experiences more contacts when the boom arm is moving up rather than down is that more risky behaviors occur during drilling and bolting when the boom arm is ascending. Based on the data collected, boom speeds greater than 13 in/sec result in a substantial increase in risk to the roof bolter operator of making contact. Speeds less than or equal to 13 in/sec are associated with a more modest relative risk of making contact, which represents a decrease in potential hazard. *Impact on Industry:* The use of such information can be quite helpful in making recommendations to machine design and task procedures to reduce the likelihood that roof bolter operators will experience injury due to contact with a moving roof bolting machine's boom arm.

1. Introduction and problem

Roof bolting is one of the basic functions and most dangerous jobs in underground coal mining. Roof bolts are the main method of roof support in mines, which is essential to ventilation and safety. After miner crews remove a section of the coal seam, roof bolting machine (see Fig. 1) operators install bolts (steel rods) to secure areas of the unsupported roof from caving in. The roof bolter operator is under constant production pressure to install as many bolts in one 8-hour shift as necessary to keep up with coal-cutting operations while remaining vigilant to all of the possible dangers.

The roof bolter operator does his or her job in a confined environment (see Fig. 2), with a limited working height (e.g., 45 in.), and in close proximity and in low visibility to a moving drill head mounted on a boom arm 72 in. long. This restricted work environment can force the operator in awkward postures for tasks that require quick reactions to avoid contact with moving machine parts. Restricted visibility due to a protection canopy and low lighting conditions further complicate the task. The Mine Safety and Health Administration's (MSHA) Health and Safety Accident Classification injury database showed an average of 660 roof bolter operator accidents per year over a 5-year period (1999–2003). This makes roof bolting a hazardous

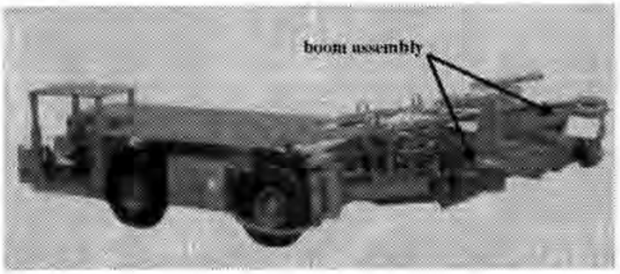

Fig. 1. Roof bolting machine (Courtesy of Fletcher Mining Equipment, Huntington, WV).

machine-related job in underground mining, representing 39% of all machine-related accidents in underground coal mines.

Protecting the safety of mine workers is of paramount importance; however, there are currently no regulations or methods of determining the safe speed of roof bolter boom arms. This article reports the initial step to define a safe speed range for a roof bolter's boom arm. MSHA accident investigation reports do not usually contain scientific information to aid in studying interactions between a machine and its operator. In addition, lab experiments with human subjects are not feasible because of safety and ethical issues. With this in mind, NIOSH researchers successfully developed a computer model (Fig. 3) that uses UGS PLM Solutions' Jack virtual human simulation software. The model generates data by means of simulation while altering several variables associated with the machine and its operator. These include coal seam height, the operator's anthropometry, work posture, choice of risky work behavior, and the machine's appendage velocity. Co-authors studied the resulting simulation database to investigate appendage speeds and decrease the number of contacts (possible injuries) to the miner by improving machine designs or operating procedures.

Experiments in other industries have provided some evidence for resolving safe machine appendage speeds for reducing potential hazards. Industries using robots exhibit

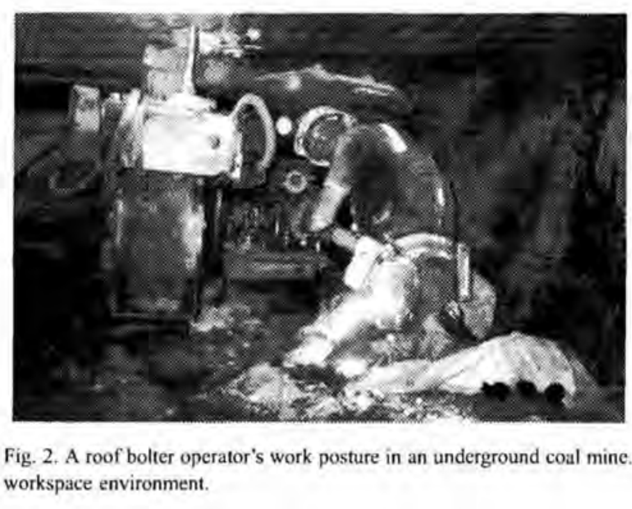

Fig. 2. A roof bolter operator's work posture in an underground coal mine workspace environment.

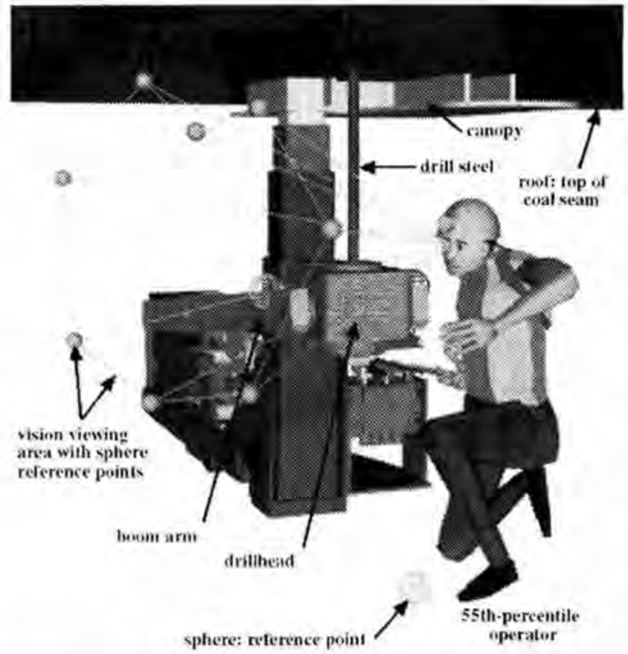

Fig. 3. A view from the display monitor of the roof bolter model.

concern for guidelines for robotics safety. Etherton (1987) reports 10 in/s as a speed whereby humans could recognize and react to perceived hazard in the system. In addition, the Occupational Safety and Health Administration (OSHA, 1987) reports that robot speeds for teach—and—repeat programming sessions are required to be slow. The current standard of American National Standards Institute (ANSI) recommends that this slow speed should not exceed 10 in/sec. However, Karwowski, Parsaei, Soundararajan, and Pogpatanasuegsa (1992) report that, with respect to the potential hazards from a moving robot arm, test subjects similarly perceive the range of slow speeds of robot motion from 8 to 16 in/s. Their study suggested that the safe slow speed of robot motions for teaching and programming purposes lies somewhere between 10 and 8 in/s, and for safe reduced speed of robot motions redefine the current recommendation of 10 in/s. Moreover, the U.S. Department of Energy (1998) states that because the teacher can be within the robot's restrictive envelop, mistakes in programming can result in unintended movement, so a restricted speed of 6 in/s is required on any part of the robot. This slower speed would minimize potential injuries to the teacher if inadvertent action or movement occurred.

This article discusses NIOSH's success in achieving its expected outcome to examine the speed range of a roof bolter boom arm for different workplace scenarios and compare statistically which scenarios are most likely to cause contacts (possible injuries) to miners. Previous studies by Klishis et al. (1993a, 1993b) on worker job performance and machinery and work environment identified miners' risk and hazard exposures while bolting. More than two dozen bolting-related problems (including specific human behaviors) were recognized as potential situations that could lead to injury or expose workers to injury. Approaches to avoid these situations were suggested and applied at mining operations to evaluate specific problems in roof bolting tasks. Turin (1995) conducted a human factors analysis of hazards related to the movement of the drill head on the boom arm of a roof bolting machine. Seven short-term recommendations to increase the safety of roof bolting operations were developed: (a) use a dead-man interlock device to cut off power to the controls when the operator is out of position; (b) place fixed barriers at pinch points and other dangerous areas; (c) provide better control guarding; (d) reduce the fast-feed speed; (e) use automatic cutoff switches for pinch points and other dangerous areas; (f) redesign the control bank to conform to accepted ergonomic principles; and (g) use resin insertion tools and resin cartridge retainers.

2. Method

2.1. Model

The model (Fig. 3) contains a virtual mine environment that includes roof bolter and operator models and experimentally mimics the virtual human and machine actions that can cause a contact. In this article, when operator limbs and a roof bolter appendage in the computer model interact and result in touching, the event is defined as a contact (see Fig. 4). Simulations of the model enable researchers to generate a database of contacts between a machine and its operator.

NIOSH's simulator uses a roof bolting machine and biomechanical human models that execute on Jack (version 1.2) simulation software. Computer simulations enable the study of multiple mine environments (i.e., seams of different heights), motions of workers (represented by virtual humans), and different work scenarios (e.g., various drilling and bolting tasks, work postures, and risky work behaviors). These studies would be dangerous and time- and cost-prohibitive if they were conducted in the field.

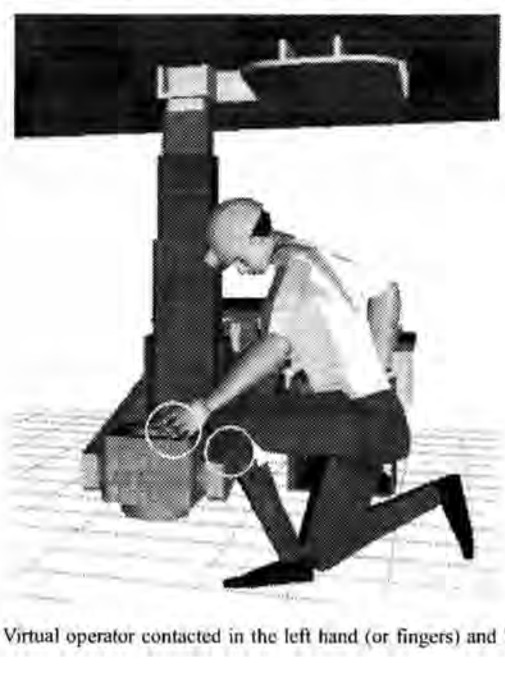

Fig. 4. Virtual operator contacted in the left hand (or fingers) and left leg.

One of the most difficult problems in using a computer simulator that generates human motions is trying to determine whether the model in the simulator accurately represents the actual mechanical system. The uncertainty and randomness inherent in machine operators' tasks can be compared to someone drinking a beverage from a cup. Lifting the cup to one's mouth and placing it back onto the tabletop exhibits some random variation in its motion path, and one could easily visualize the path of that motion. To model this random motion, the sequence of someone drinking a beverage from a cup would recur until the cup is empty. Each motion path would differ slightly even though the motions basically look alike. Likewise, in the case of a machine operator, the operator's work behaviors, motion for each behavior, and motion paths associated with each motion behavior will have some degree of randomness despite the basic task sameness. Through careful study, researchers successfully incorporated within the roof bolter model the randomness of the operator's motion and path variance within that motion. The factor of randomness gives NIOSH's simulator the capability to realistically represent the operator's motions and work behaviors while executing any machine task. In addition to random motion, the study of video tapings and captured motions of test subjects while performing the bolting task helped to determine the duration of each virtual hand motion for the model. This in turn improved the affect of the virtual operator's head, arm, hand or leg velocity, and acceleration. Ambrose (2000, 2001, 2004) and Volberg and Ambrose (2002) discuss in detail the development of random motions used in the roof bolter model.

Before collecting final simulation data, researchers used test results by Bartels, Ambrose, and Wang (2001) and Bartels, Kwitowski, and Ambose (2003) on the roof bolter model to validate and ensure that parameter assumptions made for the computer-based simulation conform to actual field practice. Training videos, in-mine observations and videos, and working with a bolter manufacturer and experts helped to determine actual bolting practice. Studies by Bartels' et al. (2001, 2003) verified the operator's response times, task motions, and field of view relative to the roof bolter's boom arm. Human subject tests with a full-scale working mockup of a boom arm were used to collect motion data that helped determine parameters for building valid and credible models. The subjects performed prescribed tasks on the mockup that mimic bolting practices and did not include risky work behaviors as described in this article. Researchers found no differences between test subjects' actual bolting practice and recommended practice (according to roof bolting training materials). During human subject data collection, risky work behaviors invalidated a test session, resulting in rerunning the test.

Two different methods to validate the model were chosen. The first method was the traditional face validity evaluation by roof bolter manufacturers and users. A questionnaire was developed and distributed to manufacturers, bolter operators, and mine inspectors. The responders were shown two animations that showed an operator-performing roof bolting tasks: one was the virtual operator produced from the motion-capture data, the other was the virtual operator created from the model. The respondents were asked to compare aspects of the animations without knowing which motion source was shown in the animation by scoring on a scale from 4 being good to 1 being poor. The virtual operator produced from the motion-capture data scored an average of 2.55, virtual operator created from the model scored an average of 2.34, and the average difference in questionnaire scoring was 0.64. Verification of the validity of the model was first implied when 14 of 15 responders agreed that the simulation animations did not differ significantly from the animations of human operators.

The second method compared the motions generated by the simulation with motion data collected on human subjects. Although the predictions of the model could not be directly compared, the accuracy of the movements used to generate "contact data" could be. The aspects of operator movements determined to be critical were the range of motion of operators and variation in those movements. The human subject movement data tended to vary greatly from individual to individual, making it impractical for a direct comparison of each individual's exact path of movement. Because the amount of movement and the variation of movement were the primary concerns, the comparisons were made between the statistical ranges by using standard deviation of movement.

Two sets of simulation data were generated from motion data of the knee and standing work postures. The first used virtual operators with anthropometric measurements identical to those of the 12 human subjects tested. Here, the data were compared on a subject-to-subject basis. The second set used operators generated from Jack software in seven different anthropometric sizes. Researchers compared data to an average of the human subjects within a 10th-percentile range (e.g., the Jack-generated 55th-percentile operator was compared to the average of the subjects in the 50th–60th percentile range).

The human subject movement data tended to vary greatly from individual to individual, making it impractical for a direct comparison of each individual's exact path of movement. Because the amount of movement and the variation of movement were the primary concerns, the comparisons were made between the statistical ranges by using standard deviation of movement.

Researchers developed two sets of test data to verify the model. One set compared Jack-generated operators' motions in different work postures in each of the anthropometrics size ranges with human subject data averaged for that range ("average" operator; e.g., the Jack-generated 55th-percentile operator was compared to the average of the subjects in the 50th–60th-percentile range). The other set compared an individual test subject's motions in different work postures with a simulation using that subject's anthropometry ("human subject" operator). The criterion for acceptance of the simulation data was less than 1.6-in difference from the human subject data, the static positional accuracy of the motion-tracking system with the resolution settings used.

Table 1 shows the percentage of range of motion data in different work postures and two operator conditions (average and human-subject) that met the acceptance criteria. The simulations run using average operators (generated from Jack software 25th-, 45th-, 55th-, 65th-, 75th-, 85th- and 92nd-percentile persons) showed a greater percentage that met the acceptance criteria. This would be expected since averaged standard deviation values were used as the input data for the actual simulation. In general, the percentage of agreement that met the criteria was very good overall (70.4%) in relation to modeling work scenarios with complexity of roof bolting.

2.2. Study population

The study population in the roof bolter model used three virtual human models representing operators that conformed to the average height of 25th-, 55th-, and 92nd-percentile males. The three virtual human models were chosen to match closely to human subject data that were collected for model verification/validation and to study the target population, which is 99% male.

2.3. Experimental design

The study evaluated contact data that the computer model generates between the machine and its virtual operator. A recorded contact event occurred when the virtual operator and machine interacted and resulted in touching. Researchers were interested only in contacts occurring when the machine appendage was moving. At no time during boom arm movement was the virtual operator positioned in a pinch-point area of the drill head or boom arm. In addition, a contact does not imply injury,

Table 1
Data that met the acceptance criteria

Work posture	Condition	Percent met criteria
Both knees	average operators	71.43
Both knees	human subject operators	63.54
Right knee	average operators	71.07
Right knee	human subject operators	62.29
Standing	average operators	69.64
Standing	human subject operators	72.66
Starting position	average operators	80.35
Starting position	human subject operators	72.22
Overall average		70.40

although it may pose the potential for the occurrence of an injury.

The model used three types of predictor variables: (a) fixed variables were used as input for simulation setup, (b) conditional variables were randomly selected within the computer model and then fixed before executing the simulation, and (c) random variables were "values" that changed during the simulation execution.

The fixed variables were:

- *Roof bolter boom arm speed*.—The boom speeds used were 7, 10, 13, 16, and 22 in/sec from MSHA's Roof Bolter-Machine Committee (MSHA, 1994). When the boom arm moved up or down for drilling or bolting, one selected speed was maintained for all events throughout the simulation execution.
- *Seam height*.—The area in which the operator had to perform the roof bolting procedure is defined as the distance from the floor to the top of the coal seam or roof, which may go beyond the top of the coal seam. The specific heights used were 45, 60, and 72 in.
- *Operator's posture while performing the roof bolting tasks*.—The work postures used were kneeling on the right knee, kneeling on the left knee, kneeling on both knees, and standing. The one selected work posture was maintained throughout the simulation execution.
- *Operator's anthropometry*.—Anthropometric data often are presented in percentiles (Kroemer, 2001); therefore, the operators' percentiles were grouped within the general population as determined by height. The percentile size operators used in the simulation were identified as 25th, 55th, and 92nd.

The conditional variables were:

- *Operator's behavior during the drilling phase of the simulation*.—Drilling behavior was randomly selected before beginning the simulation. The operator could place his/her hand on the drill steel, place his/her hand on the boom arm, place his/her hand on the drill steel then the boom arm, or the hand would not be placed on any of the machine parts. A behavior motion is a series of human motions that mimics a specific action. Researchers used Klishis et al. (1993a, 1993b) studies on worker's job performance and machinery and work environment to identify specific motions that were risky and hazardous while drilling and bolting (Table 2). Also, researchers were interested in behaviors occurring only when the machine appendage had movement.
- *Operator's behavior during the bolting phase of the simulation*.—Bolting behavior was randomly selected before beginning the simulation. The operator could place his/her hand on the bolt, place his/her hand on the boom arm, place his/her hand on the bolt then the boom arm, or the hand would not be placed on any of the machine parts.

Table 2
Behavior list for drilling a hole and installing a bolt

Operation	Work Behavior Description
Drill	Hand off the drill steel bit and than hand off the boom arm
	Hand on the drill steel bit
	Hand on the boom arm
	Hand on the drill steel bit and than hand on the boom arm
Bolt	Hand off the bolt or wrench and than hand off the boom arm
	Hand on the bolt or wrench
	Hand on the boom arm
	Hand on the bolt or wrench and than on the boom arm

- *Operator's location*.—The operator would be randomly positioned with respect to the bolter at the beginning of the simulation. The operator location is defined as the distance from a reference point on the boom arm to a reference point in the small of the operator's back. At no time during boom arm movement was the operator positioned in pinch-point areas of the drill head or boom arm.

The random variables were:

- *Boom arm direction (up or down)*.—This is the direction in which the boom arm was moving when an incident, either a contact or an avoid incident, occurred. The direction could only be one of two directions, up or down, and if the boom arm was not in motion the incident would not be used.
- *Body part (hand, arm, leg, and head)*.—This is the part of the operator involved in an incident. The parts of the body that could potentially be struck by the moving boom arm were the hand, arm, leg, or head.
- *Machine part (boom arm and drill head)*.—This is the part of the bolting machine assembly that could strike the operator. The only moving parts used for this simulation were the boom arm and drill head. The drill head is attached to one end of the boom arm.

As part of the experiment design, the operator's chance of avoiding a contact was also evaluated to ensure that an avoid incident (near-miss) would not be considered a contact. This required knowledge of when the operator sees the moving boom arm and the reaction time needed to avoid boom arm. Bartels et al. (2001) investigation provided data to determine the operator's response times and field of view relative to the boom arm.

2.4. Measurements

The data collection phase took five months to complete. The resulting simulation database contains 5,250 observations. The database represented the equivalence of actual field observations of roof bolting and corresponds to a work period of 12.15 eight-hour shifts. Collected data were recorded to a file for each simulation scenario execution. For each file, data were collected every 0.03

seconds that consist of the number of contacts made, the time when a contact happens, plus values of predictor variables (seam height, machine appendage velocity, and the operator's starting positions, work postures, risky work behaviors, operator's height, and information of his/her viewing area).

When using the virtual mine environment, separate simulations were executed on each virtual operator while performing one of the model scenarios (Table 3). Thirty-five scenarios provided the needed model combinations that varied seam heights, work postures, and boom arm speeds to mimic actual mine environments. Virtual human models that matched closely to human subject data collected for model verification/validation were given specific instructions as to how to perform the bolting tasks for each of the simulation scenarios. During the boom arm movement, the left hand's motion would be one of four possible risky work behaviors as defined in Table 2. Once the preparation for the drilling or bolt installation task was completed, the right hand was positioned on the appropriate lever that controlled the boom arm's vertical movement. In each condition, the virtual operator was required to work in the starting posture throughout the tasks. Three kneeling postures were used in the two lower seam heights. The standing posture was used in the unrestricted (high) seam. The standing postures for the two taller operators flexed more toward the right side and forward so to accommodate the workspace and proper right-hand alignment with the machine controls. This posturing was also observed during lab tests that collected human subject motion data for validating the model. The random starting position between the operator and boom arm were based on seam height and the operator's work posture according to results from human subject lab tests. Each virtual operator faced perpendicular to the long side of the boom arm, and the machine controls were always to the operator's right. The virtual operator grabbed the tools (drill steel, bolt, or wrench) with the right hand, passed the tool off to the left hand, and grabbed them with both hands to finish setting the tool in the drill head and/or hole in the mine ceiling (mine roof).

Table 3
Thirty-five possible model scenarios for each virtual operator

Scenario	Seam height (in)			Work posture				Boom speed (in/s)				
	45	60	72	RKnee	LKnee	BKnee	Stand	7	10	13	16	22
1	Y			Y				Y				
2	Y				Y			Y				
3	Y					Y		Y				
4	Y			Y					Y			
5	Y				Y				Y			
6	Y					Y			Y			
7	Y			Y						Y		
8	Y				Y					Y		
9	Y					Y				Y		
10	Y			Y							Y	
11	Y				Y						Y	
12	Y					Y					Y	
13	Y			Y								Y
14	Y				Y							Y
15	Y					Y						Y
16		Y		Y				Y				
17		Y			Y			Y				
18		Y				Y		Y				
19		Y		Y					Y			
20		Y			Y				Y			
21		Y				Y			Y			
22		Y		Y						Y		
23		Y			Y					Y		
24		Y				Y				Y		
25		Y		Y							Y	
26		Y			Y						Y	
27		Y				Y					Y	
28		Y		Y								Y
29		Y			Y							Y
30		Y				Y						Y
31			Y				Y	Y				
32			Y				Y		Y			
33			Y				Y			Y		
34			Y				Y				Y	
35			Y				Y					Y

2.5. Analysis

Data from 5,250 simulation executions were post-processed. The resulting database contains information representing variables that could influence predictions of contact incidents between the operator's body parts and the moving boom arm and drill head. The determinations of contact incidents for each simulation execution resulted in four possible occurrences:

- A contact between the machine and the operator for a person with both slow and fast reactions
- A contact between the machine and the operator for a person with just slow reactions
- An avoid incident (near-miss) where a contact occurred in the simulation, but post analysis determined that the operator saw the bolter boom arm and had fast enough reactions to get out of the way of (avoid) the contact
- A complete simulation execution where no contacts or avoid incidents occurred (none)

A simulation execution would continue until completion even though it was possible for a single simulation to have multiple contacts and avoids. The presence of multiple incidents in a single simulation execution meant that data analysis could be done on either a data set containing avoids and all contacts (all of the contacts) or one incident per simulation execution (one run/one contact). Consequently, researchers made two separate sets of data from the initial post processed database. Co-authors considered the one run/one contact data set to be more accurately representative of the real-world situation, as an operator would most likely stop or at least pause after being struck with a moving machine appendage.

3. Results and discussion

The following section contains results from frequency and cross-tabulation, and survival analyses. All analyses were conducted using only the occurrences for the operator with slow reactions that included one contact per simulation executions (one run/one contact). Analysis also shows that the difference between slow and fast reaction times of the operator did *not* significantly affect the outcome of the simulation (Table 4). The number of contact incidents for an operator with slow reactions differed from those for an operator with fast reactions by less than 1% in both data sets. The results were as expected insofar as there was a difference. There was a reasonable difference in reaction times between fast and slow operators obtained from reaction time tests on our human subjects. However, the speculation as to why a small difference in contacts might be reflected in the speed range of the boom arm being studied is that if the operator with fast reactions could not get out of the path of the boom arm, the slower operator certainly would not either. In addition, depending on the stimulus, small differences were found in some reaction time test cases in the literature search. Moreover, literature reviews were not helpful with whole-body reaction of the upper torso and limbs in confined spaces, which was a concern in our research.

3.1. Frequency

Frequency of incidents was compiled for fixed, conditional, and random variables used in the simulation in order to determine their effect on the operator (contacts between the operator and the machine).

3.1.1. Effects of fixed variables: boom arm speed, seam height, operator's work posture and anthropometry

The 60-in seam height had the most contacts, 59% of the total number of contacts and 25% of the avoid incidents. The anthropometry did not show a large difference for any one-size individual, but the 25th-percentile operator had 40% of the total contact incidents. The work posture on both knees had the greatest number of contact incidents compared to other postures (32% of the total contacts). All boom arm speeds resulted in contact incidents; the faster speeds (16 and 22 in/sec) accounted for 43% of the total contacts.

3.1.2. Effects of conditional variables: operator's work behavior and operator's work location

The hand-on-boom behavior for drilling or bolting had more contacts than any other drilling or bolting behavior. Operator location data showed three locations with increased contact incidents: 21.7, 29.9, and 30.3 in. Further sorting of operator location indicated that the increase at 21.7 in was associated with increased head incidents with the operator on both knees in a 60-in seam height. The increase in incidents at 29.9 and 30.3 in were associated with the operator in a standing position and an increase in contacts with the hand.

3.1.3. Effects of random variables: boom arm direction, body part, and machine part

The boom arm upward direction had significantly more contacts (76% of the total) and fewer avoid incidents (37% of the total) than the down direction. The hand was involved in 67% of all contact incidents. The boom arm was the closest moving machine part to the operator and accounted for 80% of all contact incidents.

3.2. Cross-tabulation

A cross-tabulation of incidents was compiled for selected variables used in the simulation in order to determine their effect on contacts between the operator and machine. The tabulation of contact incidents by variable showed which variables played the largest role in the occurrences of potential contacts to operators.

3.2.1. Effects of seam height versus random variables: boom arm direction, body part, and machine part

In comparing seam heights against boom arm direction, body part, and machine part, the following relationships were identified. Regardless of seam height, contact incidents

Table 4
Results of slow response versus fast for simulation executions

	All contacts			One contact per simulation		
	Frequency	Percent	Cumulative percent	Frequency	Percent	Cumulative percent
Slower Operator						
avoid	2,777	27.02	27.02	755	14.38	14.38
contact	5,798	56.42	83.45	2,750	52.38	66.76
none	1,701	16.55	100.00	1,745	33.24	100.00
Total	10,276	100.00		5,250	100.00	
Fast Operator						
avoid	2,768	26.94	26.94	799	15.22	15.22
contact	5,807	56.51	83.45	2,706	51.54	66.76
none	1,701	16.55	100.00	1,745	33.24	100.00
Total	10,276	100.00		5,250	100.00	

were always greater on the hand, always greater for the boom arm part of the machine, and always greater when the boom arm was moving up. The greatest number of contacts was always associated with the 60-in seam. The greatest number of contacts occurred for the 60-in seam with the boom arm moving up (46% of all contacts), the 60-in seam with contact on the hand (32% of all contacts), and the 60-in seam with contact made with the machine boom arm (47% of all contacts). The fewest number of contacts occurred for the 72-in seam with the boom arm moving down and the 45-in seam with contact made with the drill head. Zero contacts occurred with the operator's leg at a 45-in seam height and with the operator's head at a 72-in seam height.

3.2.2. Effects of operator anthropometry versus random variables: boom arm direction, body part, and machine part

In comparing subjects against boom arm direction, body part, and machine part, the following relationships were identified. Regardless of subject size, contact incidents were always greater when the boom arm was moving up, always greater on the hand, and always greater for the boom arm part of the machine. The greatest number of contacts was always associated with the 25th-percentile size, and the fewest number of contacts always occurred with the 92nd-percentile size. The greatest number of contacts occurred for the 25th-percentile size with the boom arm moving up (29% of all contacts), occurred on the hand (27% of all contacts), and involved the machine boom arm (31% of all contacts). The fewest number of contacts occurred for the 92nd-percentile size with the boom arm moving down, occurred on the arm, and involved the drill head.

3.2.3. Effects of operator's work posture versus random variables: boom arm direction, body part, and machine part

Analysts identified several relationships when comparing work posture against boom arm direction, body part, and machine part. Regardless of posture, contact incidents were always greater when the boom arm was moving up, always greater on the hand, and always greater for the boom arm part of the machine. The greatest number of contacts occurred for the both-knee work posture with the boom arm moving up (27% of all contacts), the right-knee posture with contact made with the hand (18% of all contacts), and the both-knee posture with contact made with the machine boom arm (25% of all contacts). The fewest number of contacts occurred for the standing posture with the boom arm moving down and for the standing posture with contact made with the drill head. Zero contacts occurred for the cases involving the operator's head in the right-knee, left-knee, and standing work postures and for those involving the operator's leg in the both-knee posture.

3.2.4. Effects of operator's drilling behavior versus random variables: boom arm direction, body part, and machine part

Analysts identified several relationships when comparing drilling behavior against boom arm direction, body part, and machine part. Regardless of drilling behavior, contact incidents were always greater when the boom arm was moving up, always greater on the hand, and always greater for the boom arm part of the machine. The greatest number of contacts occurred for the hand-on-boom behavior with the boom arm moving up (42% of all contacts), occurred on the hand (41% of all contacts), and involved the machine boom arm (45% of all contacts). The fewest number of contacts occurred for the hand-on-drill-steel behavior with the boom arm moving down, hand-on-drill-steel behavior with contact on the arm, and hand-on-drill-steel behavior involving the drill head part of the machine.

3.2.5. Effects of operator's bolting behavior versus random variables: boom arm direction, body part and machine part

Analysts identified several relationships when comparing bolting behavior against boom arm direction, body part, and machine part. Regardless of bolting behavior, contact incidents were always greater when the boom arm was moving up, always greater on the hand, and always greater for the boom arm part of the machine. The greatest number of contacts occurred for the hand-on-boom behavior with the boom arm moving up (26% of all contacts), occurred on the hand (27% of all contacts), and involved the machine boom arm (32% of all contacts). The fewest number of contacts occurred for the hand-on-bolt behavior with the boom arm moving down, the hand-on-boom-then-bolt behavior with contact on the arm, and the hand-on-bolt behavior with contact made with the drill head.

3.2.6. Effects of boom arm speed versus fixed variables: seam height, operator's work posture and anthropometry

For all boom speeds, the work posture on both knees had the greatest number of contacts and the standing posture had the fewest number of contacts. The greatest number of contacts occurred for the 16-in/sec speed with the work posture on both knees; the fewest number of contacts occurred for the 22-in/sec speed while standing. Regardless of boom speed, the 25th-percentile sizes had the greatest number of contacts while, regardless of speed, the 92nd-percentile size had the fewest number of contacts. The greatest number of contacts occurred for the 13-in/sec speed at the 25th-percentile size. The fewest number of contacts occurred for the 10-in/sec speed at the 92nd-percentile size. Regardless of boom speed, the 60-in seam height had the greatest number of contacts. The 72-in seam had the fewest number of contacts for all speeds except 10 in/sec, where the 45-in seam had the fewest. The greatest number of contacts was associated with the 16 in/sec speed at the 60-in seam height. The fewest number of contacts was for the 10-in/sec speed at the 45-in seam height.

3.2.7. Boom arm speed versus conditional variables: operator's work behavior and operator's work location

Regardless of boom speed, the hand-on-boom drilling behavior had the most contacts and, regardless of speed, the hand-on-boom bolting behavior had the most contacts. Regardless of speed, the hand-on-drill-steel drilling behavior had the fewest number of contacts and, regardless of speed, the hand-on-bolt bolting behavior had the fewest number of contacts. For the drilling behaviors, the greatest number of contacts was for 13 in/sec and hand on the boom arm; the fewest number of contacts was for 13 in/sec and hand on the drill steel. For the bolting behaviors, the greatest number of contacts was for 13 in/sec and hand on the boom arm; the fewest was for 10 in/sec and hand on the bolt.

3.2.8. Boom arm speed versus random variables: boom arm direction, body part, and machine part

Regardless of boom speed, contact incidents were always greater when the boom arm was moving up, always greater on the hand, and always greater for the boom arm part of the machine. The greatest number of contacts occurred at the 16 in/sec speed for the following: boom arm moving up (17% of all contacts), hand part of the body (16% of all contacts), and the boom arm part of the machine (18% of all contacts). The fewest number of contacts occurred for the 10-in/sec speed with the boom arm moving down, the 7-in/sec speed involving contact with the arm, and the 22-in/sec speed involving contact with the drill head.

3.3. Survival

One of the main interests in performing this survival analysis was to determine the impact of boom speed on the chance of experiencing a contact in these simulations of roof bolter activities. Results show that boom arm speed was the most influential factor in terms of affecting the chance of a contact occurring and the time at which such a contact might occur. Moreover, results of this analysis show that there is a significant increase in the risk of being contacted at the two highest boom speeds, 16 and 22 in/sec, compared to the lower speeds (13 in/sec or less). The former were associated with a marked, and perhaps unacceptable, increase in the risk of being contacted, whereas the risk for the latter was much more modest. From the current analysis, one can conclude that boom speeds above 13 in/sec entail significant chance of being contacted. Speeds that are 13 in/sec or below result in a much lower exposure to being contacted, which represents a decrease in potential hazard.

Covariates such as operator work behaviors (placing the hand on the boom, drill steel, or bolt), work posture and seam height combinations, boom arm direction, operator location, and worker anthropometry were also significant factors in the time-to-event regression analysis. Workers were more likely to experience a contact when the boom arm was moving in an upward direction, especially early in the roof bolting task. Kneeling work postures generally resulted in increased risk of being contacted compared to standing in a 72-in seam. Kneeling on the right knee within each seam height entailed the greatest chance of a contact. Positioning of the workers farther from the boom arm resulted in a lower risk of being contacted; however, this could also affect the workers' ability to perform the roof bolting task. Larger workers were 25% more likely to make contact with the boom arm, whereas smaller workers were about 5% less likely to make contact. Drilling behaviors such as placing the hand on the boom arm or drill steel resulted in a greater chance of a contact, while bolting behaviors (occurring later in the bolting cycle) increased the time when the event occurred.

It should be noted that this survival analysis was developed using a main effects model only. It is possible that the factors examined in this report have interactive effects (for instance, boom speed could have more of an impact on the chance of being contacted when certain work postures are adopted). The large number of simulations, computational demands of running Cox regression models and of checking proportional hazard assumptions, and the large number of interactions (120) made analysis of these interactions impractical given the time constraints involved. Ambrose et al. (2005) describes in detail the technical information regarding the methods and results of the survival analysis for those interested in the technical aspects of the analysis.

4. Summary

NIOSH researchers successfully developed a computer model that generates contact data by means of simulation while exercising the model with several variables associated with the machine and its operator, such as coal seam height, the operator's anthropometry, work posture and choice of risky behavior, and the machine's appendage velocity. The resulting simulation database contains 5,250 observations. The database represented the equivalence of actual field observations of roof bolting and corresponds to a work period of 12.15 eight-hour shifts.

Analysts used data only on the occurrences for the operator with slow reactions that included one incident per simulation execution (one run/one contact). Co-authors believe the use of such simulations, treated with statistical procedures such as frequency, cross-tabulation, and survival analysis provide extremely useful tools to evaluate the hazards of tasks where it is not possible to perform experiments with human subjects.

Significant results from frequency distribution analyses showed:

- The seam height of 60-in gave the most contacts—59% of the total number of contacts and seam height 45-in gave 75% of the near misses.

- Anthropometry did show that the 25th-percentile individual had 7% more contacts than the 55th-percentile and 13% more then the 92nd-percentile.
- Operators' work posture indicated that a posture on one knee accounted for 49% of the contacts and a work posture on both knees resulted in 32%.
- The speed of the boom arm had the greatest effect on the number of contacts for the faster two boom speeds, 43%, for 16 and 22 in/s.
- The hand on boom work behavior for both drilling and bolting tasks accounted for the majority of contacts.
- The boom arm up direction had most contacts—76% of the total number of contacts and boom arm down had 63% of the avoid incidents.
- The hand is the closest body part to the moving boom arm and was associated with 67% of all contacts and the leg came in second at 15%.
- The boom arm would be the closest moving machine part to the operator and the boom arm accounted for 80% of all contacts.
- Regardless of other variables, contact incidents were always greater when the bolter arm was moving up, were always greater on the hand, and were always greater for the boom arm part of the machine. The reason why the subject experiences more contacts when the boom arm is moving up rather than moving down is due to more risky behaviors occurring during drilling and bolting when boom arm is ascending.

Significant results regarding boom speed from cross-tabulation analyses showed:

- Regardless of boom speed, boom arm up direction experienced more contacts than did boom arm down.
- In addition, the boom arm up direction had most of its contacts in the two higher speeds, 22% during speed 16 in/s and 21% during speed 22 in/s.
- Regardless of speed, the operator's hand experienced more contacts than did other body part.
- In addition, the hand had most of its contacts; 21% during speed 13 in/s and 24% during speed 16 in/s.
- The boom arm experienced more contacts than did other machine part and had most (22%) of their contacts during both speeds 16 and 22 in/s.
- Both knee work posture experienced more contacts than did other postures and had most (23%) of their contacts during speed 16 in/s.
- The 25th-percentile operators experienced more contacts than did other operator sizes and had most (22%) of their contacts during speed 13 in/s.
- Regardless of speed, the hand on boom work behavior during drilling and bolting tasks experienced more contacts than did other behaviors.
- In addition, drilling task had most (24%) of their contacts during speed 13 in/s and bolting had most (22%) of their contacts during the same speed.
- The 60-in seam experienced more contacts than did other seam heights and had most (22%) of the contacts during speed 16 in/s.

Results of a survival analytic approach:

- Results suggested that controlling the boom speed is the most important factor in determining the chance of an operator making contact.
- Also, boom speed was the most influential variable for explaining the time to an event (contact) occurring.
- Increases in boom speed resulted in increased chance of a contact throughout the period of the simulation.
- The chance of being contacted at the higher speeds, 16 and 22 in/s, was generally 2 to 4 times greater than at 13 in/s, and 4 to 8 times greater than at 10 in/s.
- Based on the data collected in this simulation analysis, a boom arm speed greater than 16 in/s resulted in a substantial increase in the chance of the boom arm making contact with the roof bolter operator.
- In addition, results showed that speeds less than or equal to 13 in/s resulted in a smaller chance of being contacted, which represents a decrease in potential hazard.

Acknowledgments

The authors gratefully acknowledge the following colleagues at the NIOSH Pittsburgh Research Laboratory: Joseph P. DuCarme, Mary Ellen Nelson, Albert H. Cook, George F. Fischer, Albert L. Brautigam provided technical expertise in the design and fabrication of the roof bolter mockup and platform, and the associated electrical and hydraulic control systems. E. William Rossi provided technical support in operating the motion tracking and data collection system. Mary Ellen Nelson, Albert H. Cook, and Mary Ann Rossi assisted in the lab human subject tests.

References

Ambrose, D. H. (2000). A simulation approach analyzing random motion events between a machine and its operator. *Proceedings of the SAE—Digital Human Modeling for Design and Engineering Conference in Dearborn, MI, June 6–8, paper No. 2000-01-2160*. Warrendale, PA: Society of Automotive Engineers International (SAE).

Ambrose, D. H. (2001). Random motion capture model for studying events between a machine and its operator. *Proceedings of the Society for Modeling and Simulation International, Advanced Simulation Technology Conference in Seattle, WA, April 22–26* (pp. 127–131).

Ambrose, D. H. (2004). *Developing random virtual human motions and risky behaviors for studying anthropotechnical systems (IC 9468)*. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Ambrose, D. H., Bartels, J., Kwitowski, A., Helinski, R. F., Gallagher, S., McWilliams, L. J., & Battenhouse, T. R. (2005). *Mining roof bolting* *machine safety: A study of the drill boom vertical velocity (IC 9477)*. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Bartels, J. R., Ambrose, D. H., & Wang, R. (2001). *Verification and validation of roof bolter simulation models for studying events between a machine and its operator.* Proceedings of the society of automotive engineering international (SAE)—digital human modeling for design and engineering conference, paper No. 2001-01-2088 Warrendale, PA.

Bartels, J. R., Kwitowski, A. J., & Ambrose, D. H. (2003). *Verification of a roof bolter simulation model. Technical paper 2003-01-2217* (pp. 1–7). Warrendale, PA: Society of Automotive Engineers, Inc.

Department of Energy [DOE]. (1998). *OSH Technical Reference, Chapter 1–Industrial Robots, Part 4–Work Practices, 4.1 Safeguarding Methods*, http://www.tis.eh.doe.gov/docs/osh_tr/preface.html

Etherton, J. (1987). System considerations on robot end effector speed as a risk factor during robot maintenance. *Proceedings of the Eight International System Safety Conference, New Orleans, LA* (pp. 434–437).

Karwowski, W., Parsaei, H., Soundararajan, A., & Pogpatanasuegsa, N. (1992). Estimation of safe distance from the robot arm as a guide for limiting slow speed of robot motions. *Proceedings of Human Factors and Ergonomics Society v2 36th Annual Meeting. Pub by HFES Inc., Santa Monica, CA* (pp. 992–996).

Klishis, M. J., Althous, R. C., Layne, L. A., & Lies, G. M. (1993a). *A manual for improving safety in roof bolting*. Morgantown, WV: Mining Extension Service, West Virginia University.

Klishis, M. J., Althous, R. C., Layne, L. A., & Lies, G. M. (1993b). *Coal mine injury analysis: A model for reduction through training*. Morgantown, WV: Mining Extension Service, West Virginia University.

Kroemer, K. H. E. (2001). *Ergonomics: How to design for ease and efficiency* (2nd edition). Upper Saddle River, NJ: Prentice Hall.

MSHA Staff. (1994). *Coal mine safety and health roof bolting-machine committee: report of findings*. Arlington, VA: Department of Labor, Mine Safety and Health Administration, Roof Bolting Safety, Coal Mine Safety and Health, Division of Safety.

Occupational Safety and Health Administration [OSHA]. (1987). *OSHA Instruction PUB 8-1.3 Sep 21, 1987.* Office of Science and Technology Assessment.

Turin, F. C. (1995). *Human factors analysis of roof bolting hazards in underground coal mines [Bureau of Mines publication RI 9568]*. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Center for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Volberg, O., & Ambrose, D. H. (2002). Motion editing and reuse techniques and their role in studying events between a machine and operator. *Presentation and Proceedings of the Society of Computer Simulation International (SCS) Advance Simulation Technologies Conference in San Diego, April 14–18* (pp. 181–186).