Random Motion Capture Model for Studying Events Between a Machine and its Operator

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Keywords: random human-motion, anthropometrics model, machine-operator hazards, mine safety

Abstract

This paper presents a technique for representing and analyzing random motions and hazardous events in a computer simulated three-dimensional workplace, providing machine designers and safety analysts with a new technique to evaluate ways to reduce operator-machine interaction hazards. Technical data in this paper is based upon a project striving to reduce workers' risks from being hit by underground mining machinery in a confined space. By simulating motions of an operator's random behavior and a machine's appendage, researchers can accurately identify hazards, and use that information to form safe designs for mining equipment appendage velocity. Validating the model provided improvements in the operator's optimal viewing area, work task-starting positions, and operator's motions for a more accurate random behavior. Preliminary simulation results provided (1) an interesting approach to research data gathering in that there was no need for live subjects and test sites and costs associated with experiments become insignificant and (2) that the model was versatile by showing it was capable of accurately mimicking the range collision forces versus speed, operators' size, and risk behaviors found in actual industrial situations and showed (1) that response time significantly affects the number of collisions experienced by the virtual subject and (2) that analysts must be discerning with the model and not read more from the databases than what the simulation model was designed to deliver.

INTRODUCTION

Several injuries to operators of underground coal mining equipment have led an investigation of safe velocities of a roof bolter boom arm at the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory (PRL). Researchers considered studying actual mishaps but empirical data cannot be collected from the incidents. They also considered laboratory experimentation but the complexity and danger made experimentation impractical. Therefore, a computer-based, three-dimensional solid model simulation approach is being used as the primary means to gather data on mishaps. Simulations used roof bolter machine and biomechanical human models that ran on Unigraphics Solutions-Engineering Animation Inc.'s JACK simulation software. In the computer model, mishap means two or more object properties interacting. Consequently, hazardous conditions were analyzed in virtual environments using collision detection.

The model requires input data that closely matches an actual roof bolter machine operating characteristics such as dimensions and speeds as well as data that accurately reflects human physical characteristics (see figure 1.) Researchers obtained this data using a roof bolter machine mock up and human subjects at PRL. The subjects were asked to perform prescribed motions with the mock up that simulated actual practice. Actual practice was determined through training videos, in-mine observations and videos, and working with bolter manufacturer and experts.

Figure 1. Roof Bolting Machine

The uncertainty or randomness inherent in the bolting task can be compared to someone drinking a can of beverage. The occurrence of lifting the can to one's mouth and placing it back onto the table top is considered a motion-path, and one could easily visualize the path of that motion. To model a random motion, the sequence of someone drinking from a can of beverage would reoccur until the can is empty, and each motion-path would differ slightly even though the motions look alike. So the model would incorporate the randomness of the motion and path variance by changing the values that define that motion. Thus, for a machine and operator, the operator's various risk behaviors, motions of each risk behavior, and motion-paths associated with each motion behavior and moving machine appendages have some degree of randomness. These random motion-paths give the model a realistic representation of the operator's motions and behaviors found during underground mine roof bolting.

Klishis et al study on workers job performance, machinery and work environment identified miners' risk and hazard exposures while bolting [1, 2]. More than two-dozen bolting related problems (including specific human behaviors) were recognized as potential situations that could lead to injury or exposing workers to injury. Approaches to avoid these situations were suggested and applied at mining operations to evaluate specific problems in roof bolting tasks. Turin conducted a human factors analysis of hazards related to the movement of the drill head boom of a roof-bolting machine [3]. Seven recommendations to increase the safety of roof bolting operations were developed.

BACKGROUND

Roof bolting is one of the most basic and the most dangerous elements of underground coal mining operations. It is the principle 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 operators install bolts (steel rods) to secure areas of unsupported roof from caving in. A bolter crew's typical work sequence includes: general preparation and setup, drilling a hole, and installing a bolt. General preparation is a miscellaneous category that includes setting up temporary roof supports, scaling, handling ventilation material, handling supplies, emptying dust box, examining the workplace, and rock dusting. Drilling bolt holes involves inserting the drill steel in the chuck, drilling the hole, remove the steel, adding extension steels, changing the bits. Bolt installation involves making up bolt assemblies, bending bolts, inserting bolt in the hole, aligning bolt in wrench, raising the bolt, and torque the installed bolt. The sequence repeats until a mine section's roof is secure. Roof bolting may be regarded as a fairly structured and repetitive work situation. There is an established work cycle that rarely does get followed; because, a lot of variable external influences, like variability in geology, interruptions from co-workers and supervisors, machine malfunctions, supplies variability, etc. The roof bolter operator is under consistent production pressure to install as many bolts in one 8-hour shift as possible and to work being alert to all of the dangers.

The roof bolter operator does his or her job in a confined environment, i.e. limited working height as low as 114 cm and close proximity and low visibility to a moving drill head mounted on a boom arm 182-cm in length (see figure 2.)

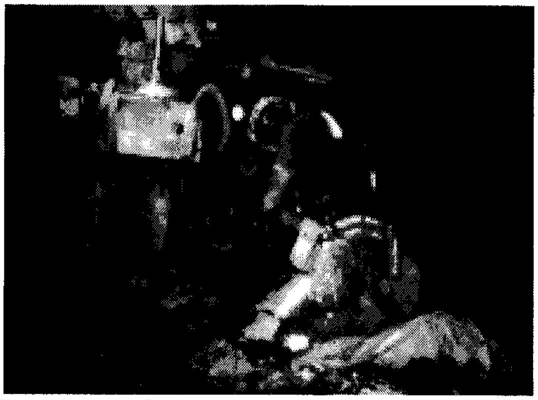

Figure 2. A Roof Bolter Operator's Work Posture and Underground Coal Mine Workspace Environment

This restricted work environment puts the operator in awkward postures for tasks that require fast reactions to avoid being hit by the moving machine parts. Restricted visibility due to a protection canopy and low lighting conditions further complicates the task. Health and Safety Accident Classification injury data base showed an average of 961 roof bolter operator incidents per year over a four year period, making roof bolting the most hazardous machine-related job in underground mining, representing 16% of all equipment related accidents in underground coal mines.

To address safety issues, MSHA (Mine Safety and Health Administration) established a roof-bolter-machine committee with members from the West Virginia Board of Coal Mine Health and Safety, NIOSH, and roof bolter manufacturers. The committee studied 613 accidents and 15 fatalities that were attributed to inadvertent or incorrect actuation of control levers while the operator was within the drill head or boom pinch-point area (see figure 3). One major outcome of this study was the realization that there is no data on safe speeds for booms operating close to workers in confined environments like an underground coal mine. The NIOSH-PRL is endeavoring to determine what boom speed minimizes the roof bolter operator's chances of injury while still doing his or her job effectively. This question becomes even more important in light of potential rules proposed by MSHA on improving the design of roof bolters.

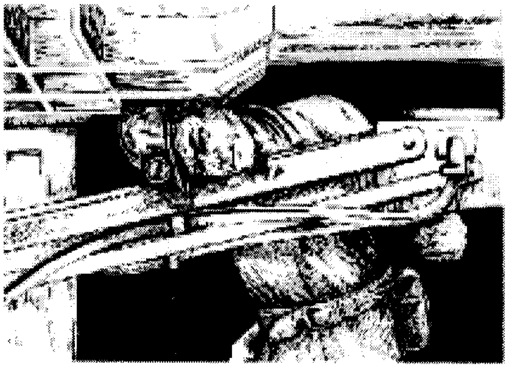

Figure 3. Artist concept of an operator caught within the boom arm and canopy pinch-point area.

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

In order to effectively answer these questions, a sufficient number of studies must be conducted to collect data on mishaps that cover 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 by the roof bolter model consist of counting mishaps. In the model, a mishap means two or more objects intersecting, e.g. the boom arm collides with the operator's hand, head or leg. Mishaps were collected in three-dimensional computer environments using collision detection. Consequently, limited laboratory experiments were needed to provide *input parameters* (accurate field of vision [4], human response in roof bolting postures, human motion envelopes of body appendages and initial work starting postures) for the roof bolter model, and to validate the computer simulations.

Early model *input parameter* values were guesses to allow the model development to continue.

MODEL DEVELOPMENT

The roof bolting operation was broken down into specific tasks. Klishis et al [1,2] observed the tasks and the amount of time spent on each task. The task list provided a guide in developing the experimental design for laboratory human subject tests and model movement for computer simulations. Basic bolting motions in the model were created from training videos, in-mine observations and videos and critiques from bolter manufacturers and experts. The simulation approach generates and collects collision data between the machine and its operator while recording with many variables, such as, the kneeing or standing posture, choice of risk behavior, anthropology and machine's appendage velocity. JACK simulation software was the simulation tool chosen to develop the roof bolter model; it is a human-centric visual simulation software package and the software's architecture lets users extend it's simulation functionality. The roof bolter model evolved from code developed in Lisp programming interface and Jack Command Language (JCL) that creates *random* human motion, *random* motion goals for the hands and torso, and *random* motion of events reflecting operator's behavior and machine appendage speed [5].

The behavior motion parameters are based on statistics of machine and human actions that could cause injuries or fatalities in a bolter's workspace. The highest percent of hazardous acts were found in two bolter tasks: drilling the hole and installing a bolt [2]. The model contains risk behaviors involving both drilling and bolt installation: (1) hand on the drill steel or bolt (see figure 4a), (2) hand on the boom arm (see figure 4b), (3) hand on the boom arm and then hand on the drill steel or bolt, and (4) hand off the boom arm and drill steel or bolt (see figure 4c).

Table 1 identifies the variables considered for the model. During simulation runs selected experimental conditions were held constant to allow researchers categorizing changing variables to make it easier for data analysis. The model allows investigators to experiment with response variable behavior (number of collisions between operator and machine) when changing the variables. The operators' response times were used in the database analysis.

Jack's human motion kinematics is well defined and validated. [6] The software's manipulation process defines how the model's operator is to achieve the final posture for the whole body or head, back, hand, arm or leg. The motion that the operator goes through to achieve a final posture is described only through Jack's motion system. For example, the manipulation values for xyz-orientation angles and xyz-positional coordinates define the final posture position of the operator. Then the human motion system's algorithm generates and animates the motion-path to achieve this final posture. Since the motion system is neither completely discrete nor completely continuous gives rise to construct a model with aspects of both discrete-event and continuous simulation. A unique, combined discrete-continuous simulation was accomplished by built-in random manipulation values within the model before transformed into a motion-path by the human motion system. Jack's motion system would reflect the variance in that motion-path as defined by these values.

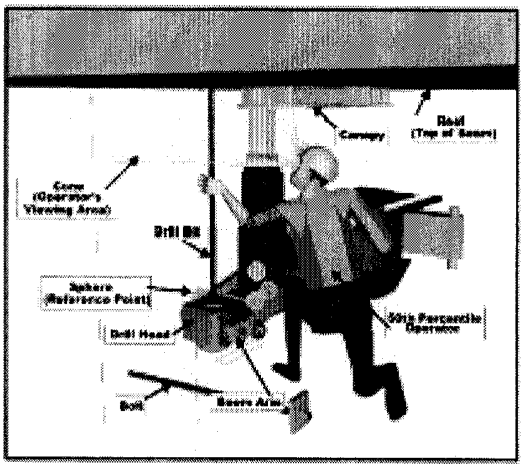

Figure 4a. Operator's risk behavior, hand on steel

Figure 4b. Operator's risk behavior, hand on boom arm

Figure 4c. Operator's risk behavior, hand off steel & boom

The uncertainty or variability inherent in the drilling and bolting tasks were incorporated into the model to effectively determine the likelihood of an operator being injured. To model the random motion, individual paths differed slightly even though the basic motions look very similar. 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 randomness. These random motions give the model a realistic representation of the operator's motions and behaviors found in actual underground coal mine roof bolting practice. 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.

VERIFYING MODEL PARAMETERS

Input parameters used to generate random motions in the model were validated. Experiments on a full scale working mock up of a roof bolter boom arm were conducted using human subjects and Ascensions Flock of Birds motion tracking system to verify operators response times and human-motion data relative to the bolter's boom arm. The tracking system position accuracy is 1.52-cm (0.6-in) and angular accuracy is 0.2 degrees. Separate vision tests were conducted using human subjects in a laboratory setup with lighting conditions found in underground coal mines. A randomized block experimental design was used. Dependent measures in the experiments 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 were used to identify those conditions where significant differences existed.

Field of vision in reduced lighting

The results of analysis were averaged for the subjects and a vision area [4] for the unique lighting conditions of underground coal mining environments developed, which accounted for the use of a miner's 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 hard hat were the most significant in terms of input to the simulation model. Typical results are shown in Table 2. Figure 5 shows the vision area when wearing the hard hat for normal lighting (21fL), reduced lighting (0.6fL) and in the original roof-bolter simulation. 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.

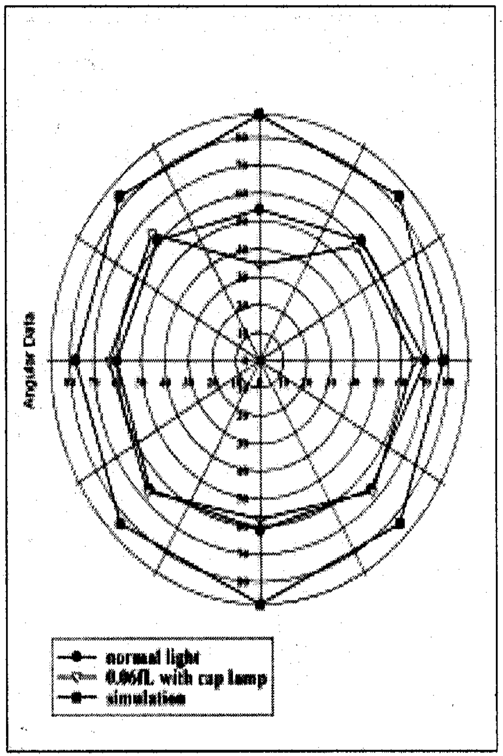

Figure 5. Vision cone viewing areas in degrees.

Human response in roof bolting postures

The motion tracking system was used to collect human response data 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. The data for the head and hands were considered the most significant for reaction characterization, because of the need of the model and Klishis et al [1,2] revealed them as most likely involved in a mishap. Table 3 gives two examples of response times calculated for each subjects' hand and head motions. The range of variation is what one might expect from human motion, maximum speed and acceleration increases as the working space increases. When the data is viewed as a function of scale, the variations in reaction parameters were reasonable to the findings of Etherton [7]. This range was averaged by anthropometrical size [8] and used to analyze data from the 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 envelops

In order to analyze *input parameters* for the virtual human model, the data from the motion capturing system were divided into six separate tasks: (1) loading the drill steel into the bolter arm; (2) drilling the roof; (3) lowering the bolter arm; (4) loading the bolt into the bolter arm; (5) bolting the roof; and (6) lowering the bolter arm. The discrete points in the data where these events occurred was 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 6.)

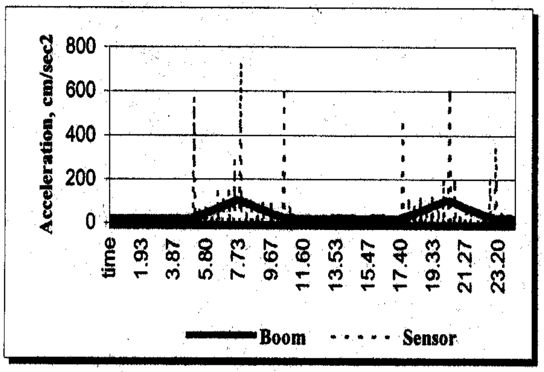

Figure 6. Determination of task starting points.

Three trials of motion data collected for each test subject were analyzed using ANOVA. For discrete 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 dependent variable. Standard deviations of bolter boom arm movement were determined and the maximum standard deviation was selected for range of variability for the virtual human movement. The boom arm has no movement in task 1 and 4; therefore, both were not critical for the object of the study. Data was classified by anthropometrical size and an example of the result is shown in Table 4.

The results of motion variance analysis produced a scattered range of variation, which at first glance does not produce a consistent pattern. When the data is viewed as a function of scale, the range of variation was small; 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 more workspace. The difference in movement between tests ranged from 2 cm to 30 cm. Model's random seed numbers are calculated from the human motion envelope data, which is close to the originally assumed variance of motion used in the random number generation in the model.

Human-machine initial start posture

Using the human motion envelops data, an average starting position for the subject's knees and back motion 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. This information provides the human model with a realistic starting position for the simulated bolting sequence and a valid range of variation in initial position for generating randomness in multiple simulation runs.

MODEL OUTPUT and SIMULATION RESULTS

The roof bolter model can generate 864 different scenarios that mimic motions of the operator and machine during the roof bolting tasks. The scenarios are defined by varying six factors: four boom arm speeds [5], two machine control configurations, three operator heights, four risk behaviors, three postures and three mine seam heights. After the model generates motions, it records collisions that happen between the machine and its operator during a simulation test run. Distances between the operator's body parts and one or more of the six reference points on the boom arm are measured and recorded. The simulation's run time when the moving boom arm enters in the operator's viewing area is recorded. All information is collected every tenth of a second throughout a simulation test run and a output function sends results to a computer file. A typical test series consists of 600 simulation test runs.

An important phase of data analysis is to create a database of each test series. This requires several steps. First, count the number of "raw" collisions that occur in each test run. Second, determine the number of "avoid" collisions in each test run that the operator could have avoided by using a predetermined human response time, taking 250 msec or 400 msec to get out of the way of a moving boom arm once seen [7]. Third, calculate the collision totals for evaluation by taking the difference between "raw" and "avoid," resulting in "hit" collisions represented as four scatter plots (see figures 7a, 7b). A scatter plot gives strong support for using regression analysis. Regression analysis (using Mircosoft Excel) shows the relationships between independent variables and one dependent variable, such as taking into account the values of the six factors in the model and predicting collision trends. With one independent variable (speed), the regression analysis plots a line of "best fit" through a scatter plot of independent-dependent (speed-collisions) value pairs.

Collisions versus speed, operator's size, and risk behaviors demonstrate the versatility found in the data obtained from the model. Response time significantly affects the number of collisions experienced by the virtual subject (see figures 8a, 8b). Also, preliminary simulation data indicates that lower seam heights have more mishaps and are more sensitive to the two response times. Factors such as age, strength or other constraints relating to a person's reaction time could be used to generate a tailored response time. Because the model's verification and validation stages are in progress, this paper reflects only preliminary simulation data.

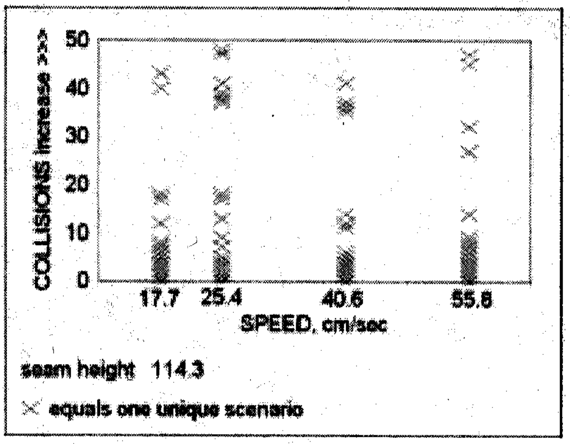

Figure 7a. Collision totals of scenarios vs boom arm speed in a 114.3 cm seam.

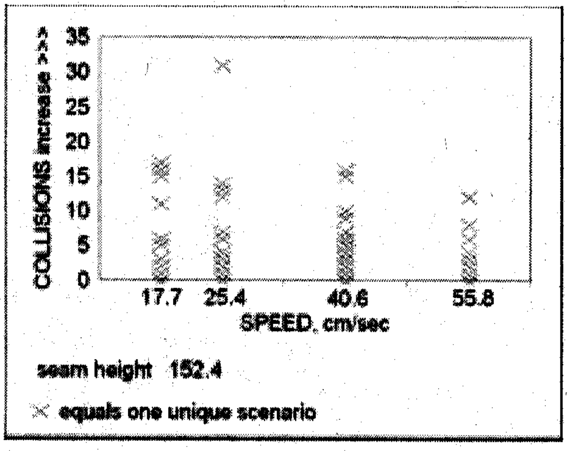

Figure 7b. Collision totals of scenarios vs boom arm speed in a 152.4 cm seam.

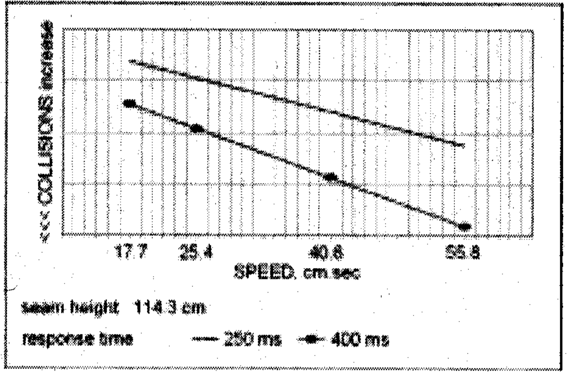

Figure 8a. Collisions vs boom arm speed and operator response time in a 114.3 cm seam.

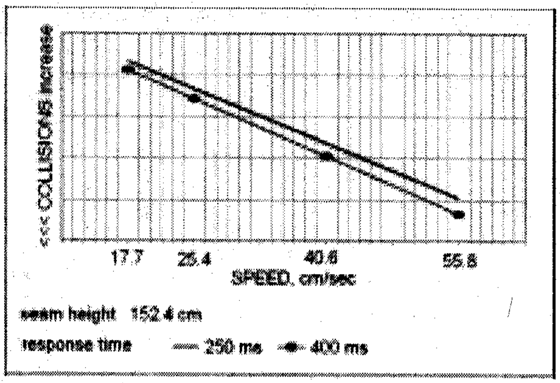

Figure 8b. Collisions vs boom arm speed and operator response time in a 152.4 cm seam.

CONCLUSIONS

Ergonomist who provided technical support for this work were overwhelmed with the infinite possibilities of simulation scenarios, because there were no limitations placed on the virtual human operator. Simulations also provided an interesting approach to data gathering in that logistics– mine sites and costs associated with experiments–became insignificant. Preliminary results showed evidence that the approach discussed in this paper is useful to study complex and instantaneous nature of mishaps between operator and machine. Actual practices, i.e., operator risk behaviors controlling roof bolters in underground mines were included in the model. Random motions of hands, arms, legs, and head make the model's human behavior realistic. Researchers developed random seed numbers for the model using data from experiments on human subjects working a roof bolter mock up.

Verification data analysis showed that following results: (1) the most significant reduction in a subject's field of vision appeared to be a result of the reduction of the viewing area caused by the hard hat; (2) the model needed the data from the head and hands; therefore considered the most significant for reaction characterization; (3) the results of motion variance analysis produced a scattered range of variation that when viewed as a function of scale, and (4) starting position information provided a realistic and valid range for the human model to initiate simulated bolting sequences.

The following general recommendations can be made upon the current outcome of this work. The model is only as good as the system it defines; basic parameters were validated using real subjects. Second, analysts must be discerning with the model and not read more from the databases than what the model was designed to deliver. Finally, the modified model will still need to be validated using field and lab studies once the correct random-motion seed numbers have been incorporated.

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ACKNOWLEDGMENTS

Bill Rossi and Ray Helinski provided technical support in operating the motion tracking and data collection system. John Bartels, Mary Ellen Nelson, Al Cook, and Mary Ann Rossi assisted in the laboratory human subject tests. John Bartels, Richard Wang, Augie Kwitowski and Mike Pazuchanics helped with post data processing. Joe DuCarme, Mary Ellen Nelson, Al Cook, George Fischer, Albert Brautigam provided technical expertise in the design and fabrication of the roof bolter mock up and platform, and associated electrical and hydraulic control systems. Ergonomist for this work were Kim Cornelius and Sean Gallagher. All of the above associates are employees of the National Institute for Occupational Safety and Health (NIOSH) at Pittsburgh Research Laboratory, Pittsburgh, PA.

DISCLAIMER

Table 1. Variables Considered in the Model.

Independent variables
Anthropometrics scale: 5th, 50th and 95th male percentile subjects
Work postures: one knee, two knees, standing, and start position from the boom arm
Operator's response time
Mine seam height: 114.3cm, 152.4 cm, and 182.8 cm
Operator's random body motion
Operator's optimal viewing area
Risk behaviors associated with drilling and bolt installation
Machine control panel configurations
Boom speeds: 17.78 cm/s, 25.40 cm/s, 40.64 cm/s & 55.88 cm/s
Dependent variables
Collisions between the operator and selected machine appendages
Distances between operator's body parts to reference points on the machine
Time-event-signal when the operator sees the moving boom arm

Table 2. Vision Cone in Reduced Lighting.

BOTH EYES	Subject 60.96-cm from focus point, becomes aware of ball at angle (deg)		
Angular path of ball , degree	21fL Normal light	.06fL	.06fL w/lamp
0 and 360	70.02	63.55	65.43
45	61.04	63.07	58.06
315	65.94	65.01	67.17
90	54.28	53.13	34.51
270	61.39	57.03	57.38
180	60.45	61.93	63.55
135	60.83	59.81	64.36
225	65.94	65.01	67.17
LEFT EYE	Subject 60.96-cm from focus point, becomes aware of ball at angle (deg)		
Angular path of ball , degree	21fL Normal light	.06fL	.06fL w/lamp
0 and 360	53.97	57.03	56.31
45	53.56	45.00	36.87
315	39.45	52.25	52.70
90	43.47	35.71	28.44
270	61.39	56.67	56.31
180	67.86	62.70	64.25
135	54.38	49.90	52.25
225	65.64	62.95	62.45
RIGHT EYE	Subject 60.96-cm from focus point, becomes aware of ball at angle (deg)		
Angular path of ball , degree	21fL Normal light	.06fL	.06fL w/lamp
0 and 360	66.80	64.25	64.47
45	59.19	60.26	61.25
315	67.43	64.36	66.04
90	42.51	48.63	35.31
270	59.66	52.91	59.04
180	49.40	48.37	51.34
135	51.34	54.78	42.51
225	65.74	62.95	62.45

Table 3. Operators' Hands and Head Response Times.

Subject #, Knee Position	Max. Head Speed, cm/sec	Elapsed Time, s	Max. Acceleration, cm/s^2			Average Speed, cm/s		
			Head	Left Hand	Right Hand	Head	Left Hand	Right Hand
Subject 6 Both	39.18	0.667	392.9	973	120.8	26.9	37.61	4.25
Left	23.19	0.411	332.7	493	626.4	16.4	21.02	22.7
Right	32.76	0.667	394.3	679	72.98	24.4	16.84	2.53
Subject 10 Both	60.67	0.622	749.1	2978	272.3	33.3	53.47	13
Left	97.90	0.733	1438	2029	533.8	49.6	69.82	17.2
Right	101.75	0.944	1796	1678	1609	54.1	31.36	24.0

Table 4. Standard Deviation of Motion for 50th-60th Percentile Operator in a 114.3-cm seam height.

Operator Posture	Bolting Cycle Task	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. Start Position on Both Knees for a 50th-60th Percentile Operator in a 114.3-cm seam height.

Measurement Location	Mean (cm.)	Standard Deviation
Distance Back	93.08	7.06
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
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