Machine Injury Prediction by Simulation Using Human Models

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ABSTRACT

This paper presents the results of a study using computer human modeling to examine machine appendage speed. The objective was to determine the impact of roof bolter machine appendage speed on the likelihood of the operator coming in contact with. A contact means two or more objects intersecting or touching each other, e.g., appendage makes contact with the operator's hand, arm, head or leg. Incident investigation reports do not usually contain enough information to aid in studying this problem and laboratory experiments with human subjects are also not feasible because of safety and ethical issues. As an alternative, researchers developed a computer model approach as the primary means to gather data. By simulating an operator's random behavior and machine's appendage velocity, researchers can study potential hazards of tasks where it is not possible to perform experiments with human subjects.

Analysis information is helpful to the mining industry in terms of making recommendations that reduce the likelihood that roof-bolter operators experience injury due to contact with a moving boom. Data analysis of roof bolter simulations show that the virtual-operator's response time has little effect on the number of contacts experienced. Based on frequency and cross-tabulation, regardless of other variables, contact incidents were always greater when the boom was moving up, were always greater on the palm, and were always greater for the boom part of the machine. Also, regardless of boom speed, the 25th-percentile-sized operators experienced more contacts than did other operator sizes. Furthermore, regardless of boom speed, the 152-cm mine seam experienced more contacts than did other seam heights tested. Results of a survival analytic approach suggest that controlling the boom speed is the most important factor in determining the risk of an operator making contact. Based on the data collected, boom speed greater than 41 cm/s results in a substantial increase in risk to the roof bolter operator and should probably be avoided. At speeds less than or equal to 25 cm/s are associated with a more modest relative risk, which represents an acceptable level of risk. Also, at speeds between 25 and 41 cm/s, there could be a particular boom speed in this range at which a significant inflection point in the relative risk estimates occurs. Based on the results, this issue needs to be addressed by future research.

INTRODUCTION

Several injuries to operators of underground coal mining equipment have led to an investigation of safe vertical velocities of a roof bolter boom-arm at the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory (PRL). Accident investigation reports from the Mine Health and Safety Administration do not usually contain enough information to aid in studying interactions between machines and their operator. Laboratory experiments with human subjects are also not feasible because of safety and ethical issues. With this in mind, researchers at PRL successfully developed for research a computer model that uses Jack® specialized computer simulation software. The model contains a virtual-mine environment that includes models of a roof bolter (Figure 1) and operator. Also, it experimentally mimics the human and machine actions that can cause a fatality or injury. The model 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, choice of risky behavior, and machine's appendage velocity. The resulting simulation database is studied by researchers to investigate appendage speeds and ways to decrease contacts or possible injuries to the miner by improving machine designs or the tasks themselves.

One of the most difficult problems faced by a model that generates human motions is trying to determine whether it accurately represents the actual mechanical system being studied. Researchers successfully incorporated within the model the randomness of the operator's motion and path variance within that motion. This randomness gives NIOSH's simulations the capability to realistically represent the operator's motions and risky behaviors found while executing any machine task. Ambrose [2000], Ambrose [2001], Ambrose [in preparation], and Volberg [2002] reports in detail the roof bolter model development and the random virtual-human motions used in the model.

Before collecting final simulation data, Bartels et al. [in preparation] test results on the roof bolter model were used to validate and ensure that parameter assumptions made for the computer-based simulation conform to actual field practice. Actual practice was determined through training videos, in-mine observations and videos, and working with a bolter manufacturer and experts. Bartels et al. [2001] and

Bartels et al. [in preparation] studies verified operators' response times, task motions, and field of view relative to the roof bolter boom-arm. Human subject's tests with a full scale working mockup of a roof bolter boom-arm (Figure 2) and motion tracking system were used for collecting motion data that helped determine parameters for building valid and credible models.

This paper discusses NIOSH's success in achieving its expected outcome to examine the speed range of a machine appendage for different workplace scenarios and compare statistically which is optimal in awarding contacts to miners. Previous studies on workers job performance, machinery and work environment has identified miners' risks and hazard exposures while bolting [Klishis et al.1993a, et al. 1993b]. 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. A field study conducted a human factors analysis of hazards related to the movement of the drill-head boom of a roof-bolting machine [Turin 1995]. Seven recommendations to increase the safety of roof bolting operations were developed.

RESEARCH

The main question that needed answered is what range of boom-arm speeds minimizes the roof bolter operator's chances of contact or possible injury while still doing his or her job safely. In order to effectively answer the question, a sufficient number of studies must be conducted to collect data on contacts and variables that influence them. A contact means two or more objects intersecting or touching, e.g., the boom-arm makes contact with the operator's hand, arm, head or leg.

A computer-based model approach was used to generate and collect contact data between the machine and its virtual-operator while recording predictor variables, such as the seam height, operator's starting positions, operator postures, risk behaviors, anthropometry, and machine appendage velocity. Data collected by the roof bolter model consist of counting contacts and recording the variables and time when a contact happens.

STUDY POPULATION

Using the capability of the Jack® software to scale operator's anthropometry, the roof bolter model used three virtual-human models representing operators that conform to 25th-, 55th-, and 92nd-percentile males. Virtual-human models were chosen to closely match human subject data that was collected for model verification and validation. Bartels et al. [in preparation] reports in detail the laboratory experiments and results that supplied parameters for the roof bolter model and virtual-human.

EXPERIMENTAL DESIGN

The roof bolting operation was broken down into specific tasks. Klishis [et. al. 1993] 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 motion scenarios for the computer simulations.

Using 3D computer simulations of virtual-environments containing a machine and virtual-human models to generate and collect data, the study evaluated the number of contact that occurred between the operator and roof bolter boom-arm while drilling a hole and installing a bolt. Data were collected every simulated frame (0.03 s). The following information was recorded per simulated frame to a separate output file for each simulation scenario execution:

- Simulated time (s),
- The operator's distance (cm) from the boom-arm to help determine operator's location from the boom prior to performing tasks,
- The boom-arm distance (cm) from a reference point to help decide boom-arm movement,
- Distance calculations (cm) between eight viewing-area reference points and a reference point on the boom-arm when the operator sees the boom, and
- A number marking sequential contacts between limbs and boom-arm was recorded for each simulated frame.

The computer model contains seven variables. The *seam height* and operator's working posture consist of 114-, 152-, 183-cm to accommodate operators' *work postures* of the right knee, left knee, both knees, and standing. Human-subject motion tests [Bartels et al. 2001 and in preparation] provided data that defined models of virtual-humans whose percentile interval ranged from 24th to the 92nd. Operator's final *anthropometry* conformed to 25th-, 55th-, and 92nd-percentile males. Also, collected from the human-subject motion tests data were the operator's *starting locations* prior to performing the motion tests. From this information unique starting location values for each subject were made as a function of seam height and postures in that seam. The four *boom-arm speeds* (18-, 25-, 41-, 56-cm/s) were selected from MSHA's roof bolting machine committee [MSHA 1994].

A behavior motion is a series of human motions that mimics a specific action. Studies on workers job performance, machinery and work environment identified miners' risk and hazard exposures while bolting [Klishis et al.1993a and 1993b]. Using this information, researchers identified specific risky *behaviors for the drilling operation* and *bolt installation*, Table 1. Researchers were interested in behaviors occurring only when the machine appendage had movement; subsequently, other risky behaviors associated with operating a roof bolter were not used. A decision algorithm was integrated [Ambrose in preparation] within the model that randomly selects what behavior to use for a simulation execution. Numerical parameters used in the algorithm came from the percent of operator actions that resulted in hazard exposure. These parameters were based on statistical observations of bolter operator actions associated with unsafe acts [Klishis et al. 1993a, p. 21].

Operator's chance of avoiding a contact was also evaluated to ensure a near-miss would not be considered a contact. This required knowledge of when the operator sees the moving boom-arm and the operator's reaction time to get out-of-the-way of the boom. Bartels et al. [2001] and Bartels et al. [in preparation] studies provided data to determine "fast" and "slow" reaction times of operators as a function of seam height, work posture and operators' anthropometrical data, Table 2.

Researchers originally used for the operator's viewing area Humantech [1996] cone with an oval shape directrix to experiment with the virtual-human's vision-tracking capabilities. For acceptable viewing in reduced lighting conditions found in underground mines, Mine Safety and Health Administration's minimum lighting requirements mandate illumination levels of 0.06 fL. The viewing area was modified from Bartels et al. [2001] test results on human subjects that determined the optimal viewing area and accurate field of vision for the virtual-human in underground mines, Figure 3.

During simulation executions, recorded data included time of contacts and when the boom-arm is in and out of the operator's view. Subsequently, during data post-processing of the contact database, a contact-check algorithm compared time-pairings of when the boom-arm is in-view and out-of-view to determine suspected near-miss. The results provided researchers with information that identified contacts that the operator could avoid.

Table 3 summarizes the factors that were used to generate 4,200 observations that comprised the research database. Noting that the database represents the equivalence of actual field observations of roof bolting work in underground coal mines for a period of 9.48 eight-hour shifts. When using the virtual-environment, simulations were executed on each percentile-operator while performing 1 of 28 possible roof bolting scenarios. Twenty-eight scenarios consisted of combinations of the seam height, work posture, and boom-arm speed.

MEASUREMENTS

Virtual-operators were given specific instructions as to how to perform the bolting tasks for each of the simulation scenarios. In each condition, the operator was required to work in the starting posture throughout the tasks. Three kneeling postures were used only in the lower seams. The standing posture was used in the highest seam. The standing postures for the two taller operators were flexing more toward the right-side and forward to accommodate the work space and proper right-hand alignment with the machine controls. This posturing was also observed during laboratory tests that collected human subjects' motion data for validating the model. The random starting position between the operator and boom-arm were based on seam height and operator's work posture according to results from human-subject laboratory tests. Each virtual-operator faced perpendicular to the long side of the boom-arm, and the machine controls were always to his right. The virtual-operator grabbed the tools (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 (or mine roof as it is called.) 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. During the boom-arm movement, the left hand's motion would be 1 of 4 possible risky behaviors as defined in Table 2. When the virtual-operator and machine interacted and resulted in touching, the event was defined as a contact. Researchers were interested in only contacts occurring when the machine appendage was moving. Furthermore, the model included random operators' motions before and after the boom-arm appendage moved. These motions helped to improve motion accuracy through random positioning of the arm and hand just before or after appendage movement. Also, these motions made the overall model (Figure 4), when simulated, look visually realistic.

Three separate computer workstations were used in the data-gathering phase of the study. Using different workstations did not influence simulation outcomes and a copy of the simulation model ran perfectly on all computers. No changes or modifications to the model were necessary for any of the workstations used in data collection. The data collection phase took four months to complete.

RESULTS

The simulation would continue to 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.

Table 4 compares the two sets of data. This comparison showed that the source of incidents and the relationship of the variables associated with the incident did not differ significantly for the two. The one-run-one-contact data set was also considered by researchers 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. The set of data containing only one-run-one-contact also lent itself to other types of data analysis techniques such as survival.

Analysis also indicates that the reaction time of the operator did not significantly affect the outcome of the simulation, Table 5. The number of incidents for an operator with slow reactions differed from those for an operator with fast reactions by less than 1% in both data sets.

Ambrose et al. [in preparation] discusses in detail frequency and cross-tabulation, and survival analyses. All analysis was conducted using only the occurrences for the operator with slow reactions that included one-incident per simulation execution (one-run-one-hit).

FREQUENCY & CROSS-TABULATION ANALYSES

A table of incidents was compiled for variables used in the simulation in order to determine their effect on operator injuries such as contacts between the operator and machine. Frequency analysis is the simplest method to observe how different categories of values are distributed in the sample database. Customarily, if a data set includes any categorical data (e.g., seam heights, appendage speeds, work postures, etc.) then one of the first steps in the data analysis is to compute a frequency table for those variables. Cross-tabulation is a combination of two (or more) frequency tables arranged such that each cell in the resulting table represents a unique combination of specific values of cross-tabulated variables. Thus cross-tabulation allows researchers to examine frequencies of observations that belong to specific categories on more than one variable. By examining these frequencies, researchers can identify relations between cross-tabulated variables and provide information on trends in preparation to use other statistical approaches on the database.

Summary

- In summary, the frequency-fixed variable analyses indicated that following:
    - Speed of the boom-arm have the greatest effect on the number of incidences with a sharp increase in contacts for faster boom speeds 58% for 41 and 56 cm/s.
    - 152-cm seam height had the most contacts, 60% of the total number of contacts, and 30% of the near misses.
    - Operators' posture indicated that a posture on both knees was the worst with 33% of the incidents.
    - Anthropometry did not show a large difference for any one size individual; however, the 25th-percentile individual did have slightly more incidents than the other size individuals.
- In summary, the frequency-random variable analyses indicated that following:
    - The palm is the closest body part to the moving boom-arm and was associated with 71% of all incidents.
    - The boom would be the closest moving machine part to the operator and accounted for 77% of all incidents.
    - Regardless of other variables, contact incidents were always greater when the bolter arm was moving up, were always greater on the palm, and were always greater for the boom part of the machine.
- In summary, the frequency-conditional variable analyses indicated that following:
    - Considering operator behavior during drilling, 49.9% of all contacts occurred for the hand-on-boom behavior with the arm going up.
    - Considering operator behavior during drilling, 45.6% of all contacts occurred for the hand-on-boom behavior with contact being made with the palm part of the body.
    - Considering operator behavior during drilling, 49.5% of all contacts occurred for the hand-on-boom behavior with contact being made with the machine boom.
- In summary, the cross-tabulation-fixed variable analyses indicated that following:
    - Regardless of boom speed, the 25th-percentile sized operators experienced more contacts than did other operator sizes.
    - Regardless of boom speed, the 92nd-percentile sized operators experienced fewer contacts than did other operator sizes.
    - Regardless of boom speed, the 152-cm seam experienced more contacts than did other seam heights.
- In summary, the cross-tabulation-fixed-random variable analyses indicated that following:
    - Considering all contacts, 43.8% occurred for the152-cm seam with the arm going up.
    - Considering all contacts, 46.9% occurred for the 152-cm seam with contact being made with the machine boom.

SURVIVAL ANALYSIS

Survival analysis is known as event history analysis or time-to-event analysis in the social sciences. Time-to-event data are increasingly common in health research, particularly in longitudinal or cohort studies where the onset of certain health outcomes is observed. Analyses of this type involve the amount of time (such as to the first contact) that a subject is at risk while under observation. Using analysis techniques on longitudinal event data will probably come up against two intractable problems: (1) censoring, the sample database contains some cases that do not experience an event (contact) and (2) many predictor variables (e.g., seam height, appendage speed, work postures) change in value over time. Survival methods are explicitly designed to deal with censoring and time-dependent covariates in a statistically correct way.

A Cox regression model (time-to-event regression analysis) was conducted to evaluate the factors influencing the time to a worker being hit. The hypothesized time-to event regression model is given: $h(t|z) = h_o(t|z)\exp(\beta_1 z_1 + \beta_2 z_2 + \beta_3 z_3 + \beta_4 z_4 + \beta_5 z_5 + \beta_6 z_6 + \beta_7 z_7 + \beta_8 z_8 + \beta_9 z_9 + \beta_{10} z_{10} + \beta_{11} z_{11} + \beta_{12} z_{12} + \beta_{13} z_{13} + \beta_{14} z + \beta_{15} z_{15} + \beta_{16} z_{16} + \beta_{17} z_{17} + \beta_{18} z_{18} + \beta_{19} z_{19})$ where: β_k = coefficients for variables used in the model, z_1 = boom speed 25 cm/s, z_2 = boom speed 41 cm/s, z_3 = boom speed 56 cm/s, z_4 = drilling behavior: hand on drill, z_5 = drilling behavior: hand on boom, z_6 = drilling behavior: hand on drill and boom, z_7 = Boom moving upwards, z_8 = Posture/Seam: right knee/144-cm, z_9 = Posture/Seam: right knee/152-cm, z_{10} = Posture/Seam: left knee/144-cm, z_{11} = Posture/Seam: left knee/152-cm, z_{12} = Posture/Seam: both knees/144-cm, z_{13} = Posture/Seam: both knees/152-cm, z_{14} = bolting behavior: hand on bolt, z_{15} = bolting behavior: hand on boom, z_{16} = bolting behavior: hand on bolt and boom, z_{17} = Operator Location (cm), z_{18} = 25th-percentile worker, z_{19} = 95th-percentile worker.

A forward selection procedure was used in model development. Treatment (z_1) was forced into models beyond the first (univariate) step. In subsequent steps, variables were selected for inclusion on the basis of the Akaike Information Criterion (i.e., the model whose variable resulted in the lowest Akaike Information Criterion (AIC) was selected at each successive step of the model-building process). The model-building process ceased when the lowest AIC for a step was greater than the lowest AIC obtained in the previous step.

A primary assumption of the time-to-event regression model was that the hazard proportions associated with model variable comparisons did not differ significantly with respect to time during the period of analysis. This assumption was checked for all variables at the univariate stage of the model-building process. If the assumption did not appear tenable, the interaction between the variable and the natural logarithm of time was included in the model whenever that variable was entered into the regression models. A final check of the proportional hazards assumption was performed once the final model was determined.

Probabilities that risk ratios were significantly different from one were calculated using the Wald statistic for covariates with one degree of freedom. Probabilities for variables with multiple degrees of freedom were obtained by subtracting the log likelihood for the reduced model from the full model, and obtaining a chi-square with the appropriate degrees of freedom. Alpha levels were set at 0.05 for all cases.

Summary

One of the primary 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 indicate that boom-arm speed factor was the most influential 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 indicate that there is a significant jump in chance of being contacted at the two highest boom speeds – 41 and 56 cm/s – compared to the lower speeds examined – 18 and 25 cm/s. The former were associated with a marked, and perhaps unacceptable, increase in the amount of chance of being contacted, while the chance for the latter is much more modest. What cannot be evaluated from this data is the dangers associated with speeds in the intermediate range – between 25 and 41 cm/s. It is quite conceivable that there exists a point at which a sharp increase in chance of being contacted is evident. If such an inflection point is found, it could provide the basis for a design criterion that could provide a reasonable degree of protection to workers. All that can be said from the current analysis is that boom speeds above 41 cm/s seem to entail significant chance of being contacted, and should probably be avoided. Speeds 25 cm/s or below result in a much lower exposure to being contacted, which represents an acceptable hazard level.

Covariates such as operator behaviors (placing their hands on the boom, drill, or bolt), postures and seam height combinations, boom direction, operator location and worker anthropometry also were significant factors in the time-to-event regression analysis. Workers were more likely to experience a contact when the boom was moving in an upward direction, especially early in the roof-bolting task. Kneeling postures generally resulted in increased chance of being contacted compared to standing in a 182-cm seam; however, kneeling on the left knee in a 144-cm seam much lower chance of making contact. Kneeling on the right knee in the same seam height entailed significantly higher chance of being contacted. Positioning of the workers further from the boom resulted in lower chance of being contacted; however, this could also impact the workers ability to perform the roof bolting task. Larger workers were 20% more likely to be contacted, while smaller workers were about 6% less likely to make contact with the boom. Drilling behaviors such as placing the hand on the boom or drill resulted in a higher risk, while bolting behaviors (occurring later in the bolting cycle) increased the time to and event occurring.

It should be noted that this survival analysis was developed using a main effects model only. It is quite 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 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) possible make analysis of these interactions extremely time consuming.

CONCLUSION

Researchers at PRL successfully developed a computer model that generates 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 machine's appendage velocity. The resulting simulation database is comprised of 4,200 observations. The database represented the equivalence of actual field observations of roof bolting and corresponds to a work period of 9.48 eight-hour shifts.

Data analysis was conducted using only the occurrences for the operator with slow reactions that included one-incident per simulation execution (one-run-one-contact). Researchers on this project 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. Results of this analysis could help in terms of making recommendations that reduce the likelihood that roof-bolter operators experience injuries due to contact with a moving boom.

Analysis indicates that the reaction time of the operator did not significantly affect the outcome of the simulation. The number of incidents for an operator with slow reactions differed from those for an operator with fast reactions by less than 1% in both data sets.

Significant results from frequency analyses showed that the speed of the boom-arm have the greatest effect on the number of incidents with a sharp increase in contacts for faster boom speeds 58% for 41 and 56 cm/s. The seam height of 152-cm gave the most contacts, 60% of the total number of contacts, and 30% of the near misses. Operators' posture indicated that a posture on both knees was the worst with 33% of the incidents. Anthropometry did not show a large difference for any one size individual; however, the 25th-ercentile individual did have slightly more incidents than the other size individuals. The palm is the closest body part to the moving boom-arm and was associated with 71% of all incidents. The boom would be the closest moving machine part to the operator and accounted for 77% of all incidents. Regardless of other variables, contact incidents were always greater when the bolter arm was moving up, were always greater on the palm, and were always greater for the boom part of the machine. Significant results from cross-tabulation analyses showed that regardless of boom speed, the 25thpercentile sized operators experienced more contacts than did other operator sizes. Regardless of boom speed, the 152-cm seam experienced more contacts than did other seam heights.

Results of a survival analytic approach 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 in terms of 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 – 41 and 65 cm/ is generally 5 to 8 times greater than at 25 cm/s, and 8 to 25 times greater than at 18 cm/s. Based on the data collected in this simulation analysis, the boom-am speed greater than 41 cm/s result is a substantial increase in the chance of making contacted with the roof bolter. Also results showed that at speeds less than or equal to 25 cm/s resulted in a more modest chance of being contacted, which represents an acceptable hazard level.

Other factors have also been shown to have a significant influence on the chance of being contacted, as detailed in the report. Researchers on this study do plan to continue examination of the data and to uncover significant interactions should they exist. While the current research cannot speak to the dangers associated with speeds between 25 and 41 cm/s, there could be a particular boom speed in this range at which a significant inflection point in the relative contact estimates occurs. Based on the results of this data analysis, this is an issue that needs to be addressed by future research.

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Table 1- Behavior list for the drilling the hole and installing a bolt

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

Table 2 - Reaction times of operators used in the roof bolter model

seam height cm (in)		114 (45)						152 (60)						183 (72)	
work posture		right knee		left knee		both knees		right knee		left knee		both knees		standing	
reaction time (ms)		fast	slow	fast	slow	fast	slow	fast	slow	fast	slow	fast	slow	fast	slow
operator percentile	25th	436	736	356	656	376	676	370	670	376	676	356	656	374	674
	55th	401	701	366	666	397	697	333	633	392	692	353	653	376	676
	92nd	330	630	384	684	349	649	403	703	424	724	375	675	388	688

Table 3 - Factors that determined the number of observations per seam height

observation totals	seam height cm	factors			
		operator	boom speeds	work postures	simulation executions
1,800	114	3	4	3	50
1,800	152	3	4	3	50
600	183	3	4	1	50
overall 4,200					

Table 4 - Comparison of one-contact per execution versus all contacts

		ONE-RUN-ONE-CONTACT		ALL Contacts	
variable	response	near misses	contacts	near misses	contacts
SEAM HEIGHT	slow	114>152>183	152>114>183	114>152>183	152>114>183
(cm)	fast	114>152>183	152>183>114	114>152>183	152>183>114
SUBJECT SIZE	slow	55>25>92	25>55>92	25>55>92	25>55>92
(anthropometeric percentile)	fast	55>25>92	25>55>92	25>55>92	25>55>92
POSTURE	slow	L>R>B>S	B>R>L>S	L>R>B>S	B>R>L>S
L-left,R-right,B-both,S-stand	fast	L>R>B>S	B>R>L>S	L>R>B>S	B>R>L>S
SPEED	slow	25>56>41>18	41>56>25>18	25>41>18>56	41>56>18>25
(cm/sec)	fast	25>41>56>18	41>56>25>18	25>41>56>18	41>56>18>25
DRILLING BEHAVIOR	slow	B>DB>N>D	N>B>BD>D	B>DB>N>D	B>DB>N>D
Hand on B-boom,D-drill,N-none	fast	B>DB>N>D	N>B>BD>D	B>DB>N>D	B>DB>N>D
BOLTING BEHAVIOR	slow	N>B>BT>BBT	N>B>BBT>BT	N>B>BBT>BT	B>BBT>N>BT
Hand on B-boom,BT-bolt,N-none	fast	N>B>BT>BBT	B>BBT>N>BT	N>B>BT>BBT	B>BBT>N>BT
BOOM DIRECTION	slow	U>D	U>D	U>D	U>D
D-down,U-up	fast	U>D	U>D	D>U	U>D
BODY PART	slow	P>L>A>H	P>A>H>L	P>L>A>H	P>A>H>L
A-arm,L-leg,H-head,P-palm	fast	P>L>A>H	P>A>H>L	P>L>A>H	P>A>H>L
SIDE	slow	L>R>H	L>H>R	L>R>H	L>H>R
L-left,R-right,H-head	fast	L>R>H	L>H>R	L>R>H	L>H>R
MACHINE PART	slow	B>D	B>D	B>D	B>D
B-boom,D-drill	fast	B>D	B>D	B>D	B>D

Table 5 - Results of slow response versus fast for simulation executions

Slow operator, all incidents				**Slow operator, one incident pre simulation**		
	Frequency	Percent	Cumulative	Frequency	Percent	Cumulative
avoid	1657	27.62	27.62	735	17.50	17.50
contact	2320	38.67	66.28	1442	34.33	51.83
none	2023	33.72	100.00	2023	48.17	100.00
Total	6000	100.00		4200	100.00	
Fast operator, all incidents				**Fast operator, one incident pre simulation**		
	Frequency	Percent	Cumulative	Frequency	Percent	Cumulative
avoid	1661	27.68	27.68	770	18.33	18.33
contact	2316	38.60	66.28	1407	33.50	51.83
none	2023	33.72	100.00	2023	48.17	100.00
Total	6000	100.00		4200	100.00	

Table 6 - Final Model Detail

Variable	df	Beta	SE	p-value	RR	95% CI
BOOM SPEED (cm/s)						
25	6	-.970	.445	.029	.379	.158-.907
41		-.320	.551	.561	.726	.247-2.136
56		1.276	.704	.070	3.582	.901-14.237
25 *ln(time)		.581	.168	.001	1.788	1.287-2.483
41 *ln(time)		.911	.225	.000	2.487	1.599-3.869
56 *ln(time)		.509	.299	.089	1.664	.925-2.993
DRILL BEHAVIOR						
Hand on Drill	6	7.999	.807	.000	2977.250	612.769-14465.512
Hand on Boom		9.214	.587	.000	10040.63	3174.801-31754.527
Hand on Both		9.372	.741	.000	11754.22	2749.898-50242.489
Hand on Drill*ln(time)		-2.359	.291	.000	.095	.053-.167
Hand on Boom*ln(time)		-2.618	.197	.000	.073	.050-.107
Hand on Both*ln(time)		-2.637	.275	.000	.072	.042-.123
BOOM UP						
Boom Up	2	5.979	.409	.000	394.968	177.351-879.610
Boom Up*ln(time)		-1.693	.155	.000	.184	.136-.249
POSTURE/SEAM (cm)						
Right 114	12	-5.649	.746	.000	.004	.001-.015
Right 152		-2.052	.567	.000	.129	.042-.390
Left 114		1.486	1.659	.370	4.420	.171-114.110
Left 152		-2.309	.565	.000	.099	.033-.301
Both 114		-2.852	1.025	.005	.058	.008-.430
Both 152		-1.893	.585	.001	.151	.048-.474
Right 114*ln(time)		2.534	.304	.000	12.599	6.947-22.849
Right 152*ln(time)		.921	.226	.000	2.513	1.614-3.911
Left 114*ln(time)		-.789	.744	.289	.455	.106-3.911
Left 152*ln(time)		1.077	.218	.000	2.936	1.916-4.499
Both 114*ln(time)		1.115	.434	.010	3.051	1.304-7.136
Both 152*ln(time)		.888	.217	.000	2.430	1.590-3.715
BOLTING BEHAVIOR						
Hand on Bolt	3	-.167	.087	.055	.846	.713-1.004
Hand on Boom		-.465	.072	.000	.628	.545-.724
Hand on Both		-.544	.083	.000	.580	.494-.682
OPERATOR LOCATION	1					
Operator Location		-.028	.009	.002	.972	.955-.989
ANTHOPOMETRY						
25th -percentile	2	-.060	.078	.438	.942	.808-1.096
92nd -percentile		.180	.072	.012	1.198	1.04-1.380

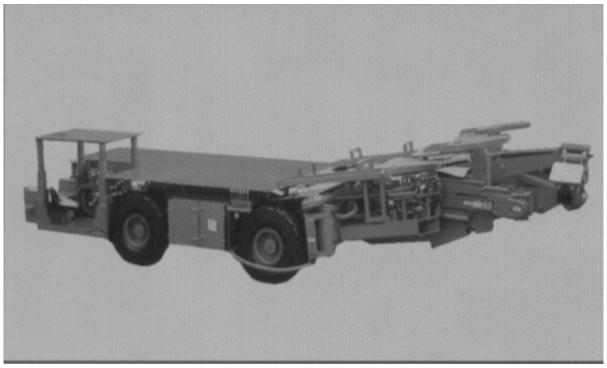

Figure 1. Actual roof bolting machine

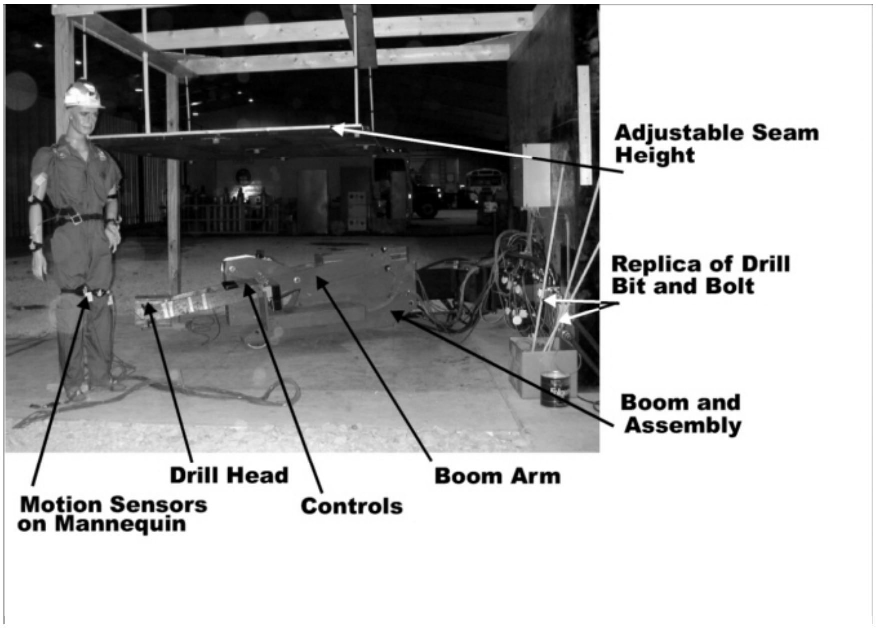

Figure 2. Full-scale wooden roof bolter boom arm setup for data collection; the mannequin illustrates motion sensor locations on human subjects

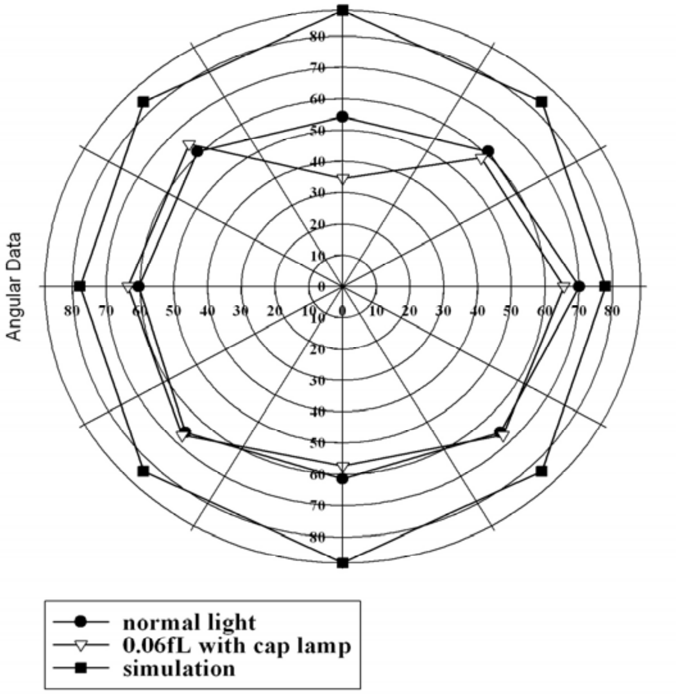

Figure 3. Angular data of the original and modified cones for the virtual-operator

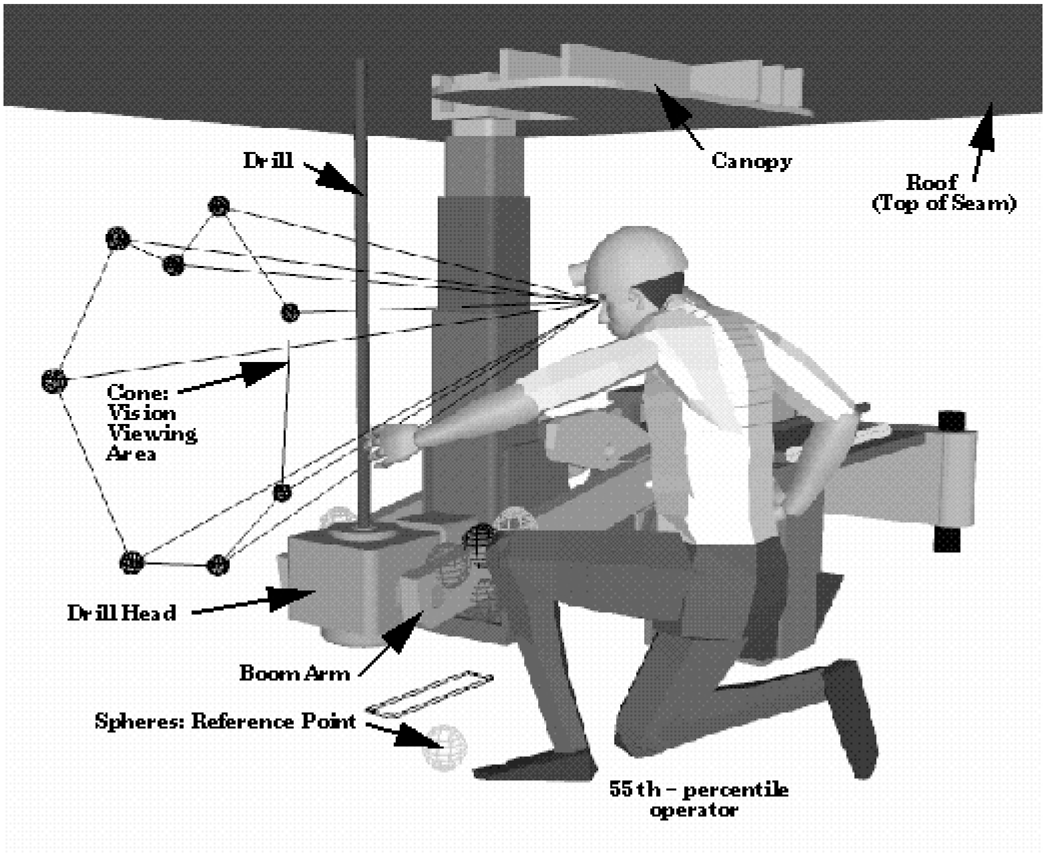

Figure 4. - A view from the display monitor of the roof bolter model