Analyzing factors influencing struck-by accidents of a moving mining machine by using motion capture and DHM simulations

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ABSTRACT

Remote operation of continuous mining machines has enhanced the health and safety of underground miners in many respects; however, numerous fatal and non-fatal continuous miner struck-by accidents have occurred. In an effort to prevent these injuries, NIOSH researchers at Pittsburgh Research Laboratory studied the workplace relationships between continuous miner operators and various tramming tasks of the equipment using motion capture data, operator response times, and field of view data to evaluate the factors influencing operator-machine struck-by events (contact with a solid object) in a virtual mine environment. It is not feasible (nor ethical) to use human subjects to directly evaluate factors that precipitate such injuries. However, use of motion analysis data and digital human models can facilitate analysis of struck-by accident risk by allowing investigators to manipulate factors that influence injury. Factors included in this study included machine speed, direction of escape, the direction the operator was facing relative to the machine, work posture, distance from machine, and operator anthropometry. Close proximity to the machine, high machine tramming speeds, a right-facing orientation and operator positioning near the tail all resulted in high risk of being struck.

INTRODUCTION

The use of digital human models (DHMs) to analyze workplace hazards and improved workplace design are becoming more prevalent among human factors and ergonomics professionals (Badler et al., 2002; Brown, 1999; Chaffin, 2002; Colombo and Cugini, 2005; Ferguson and Marras, 2005; Zhang, X. and Chaffin, D.B., 1996). These DHMs can be driven by human motion analysis techniques**,** providing a means by which human-machine interactions can be analyzed. One particular advantage of DHMs is that they can be used to evaluate the risks associated with hazardous tasks (or interaction with potentially hazardous machinery) without risk of serious injury to a person. An example of this type of situation is one where struck-by or caught-between accidents might occur when a worker is operating tramming (moving) machinery.

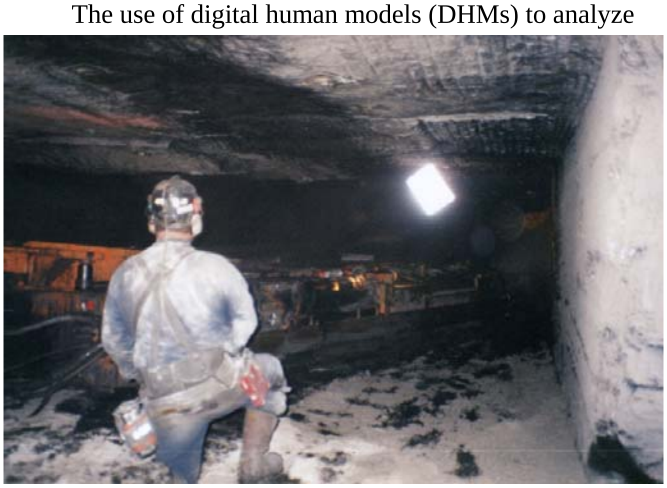

Figure 1. Continuous miner operator by tail.

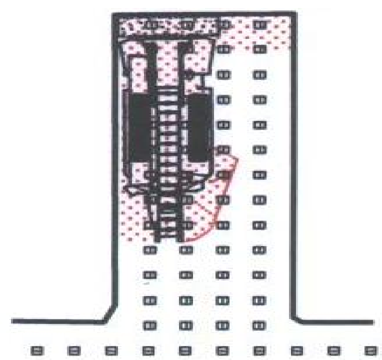

Figure 2. Red Zone around a continuous miner.

The Mine Safety and Health Administration (MSHA) reports that both fatal and non-fatal remote-control continuous miner (figure 1) accidents from 1999-2006 are averaging 254 per year during routine mining activities with the majority of accident victims working within the turning radius of moving continuous miners. The mining industry uses an educational aid called "red zones are no zones" (MSHA 2006) to help operators of remote control vehicles, such as continuous miners, to understand which areas around the machine to avoid (figure 2). However, fatalities and injuries still continue as results of contact with moving machines.

MSHA is interested in reducing injuries and fatalities attributed to the operation of continuous mining machines (Clark et al., 1998, Colley et al., 2006). As recently as February 2006, MSHA posted on its website information regarding protection of continuous miner operators by using proximity warning devices to help recognize the red-zone strategy.

In an effort to better understand the influence of these issues on the risk of injury, it was decided that a DHM using motion capture of operator movements would be a useful methodology. The purpose of this investigation was to analyze factors influencing struck-by accidents during tramming of a continuous mining machine using DHM simulations driven by actual human motion analysis using a variety of human subjects, postures, facing orientations, environmental constraints, and mining machine operational characteristics.

METHOD

Motion Analysis Data

Ten male subjects aged 32-59 years were recruited from local mines to perform realistic movements in a laboratory setting (figure3) that mimic getting out of the way of a moving

Figure 3. Laboratory test setup; a subject finishes a trial run.

continuous mining machine. Experienced operators were used because they are accustomed to the unique movements and

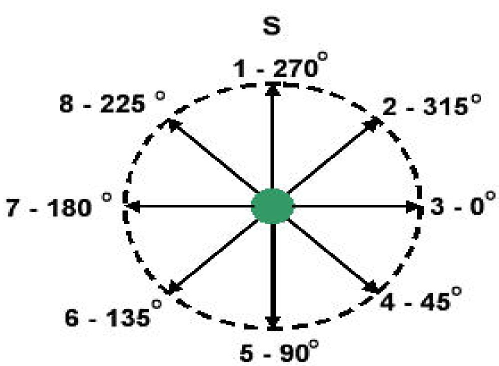

Figure 4 . Test area layout showing path number and orientation in degrees.

postures required in the mining. The subject's motions were measured by recording them using Motion Analysis Corporation's (MAC) motion tracking and capturing system. MAC is an optical system that uses infrared sources and cameras to track reflective markers placed on a test subject. From measured infrared reflective characteristics, each marker position and orientation is computed by EVaRT, specialized MAC software that converts and records this information for future analysis.

Human motion data were obtained for various operator work postures and escape paths (directions) typically used when operators are tramming mining equipment such as continuous miners. The capture session was conducted for a posture of kneeling on both knees, a squatting posture and a standing posture that represented seam heights of 36-, 48- and 60-inch, respectfully. At a given signal, a test subject moved from a starting location (see figure 4, solid circle) as quickly as possible along a given path (numbered 1 thru 8) labeled on a carpet in the test posture. The sequencing of path direction was randomized for each subject. Prior to each path movement, the subject's orientation was either facing the signal source (a researcher controlled light) or with the signal source to the subjects left or right side. The signal source also emitted an infrared signature allowing it to be captured with the motion data. When a light signal source at 'S' was turned on it cued the test subject to move. The subject stopped moving once he crossed the outer portions of the dash-circle (figure 4) on the carpet (figure 3). Each subject completed 216 trial runs to accommodate the variables of operator's work posture, facing orientation, and escape path direction.

Development of Human-machine Model and Simulation Data Collection

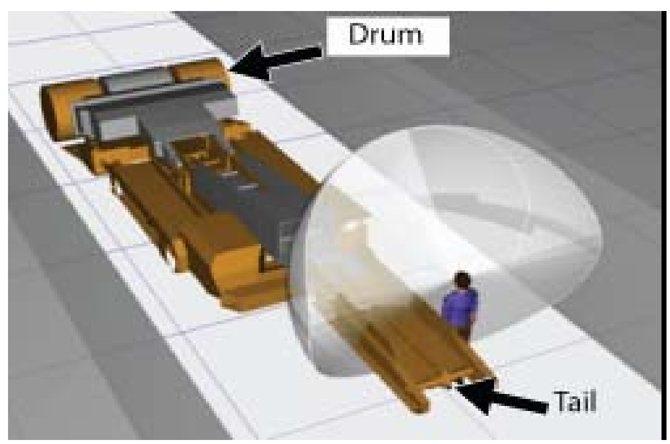

Figure 5. Model contains a continuous miner model, DHM as operator and DHM's peripheral vision views

A human-machine model (figure 5) was developed to measure parameters that would be used to predict struck-by events when the operator moves out of the way of the moving machine. The parameters included: (1) the time when the machine first begins to move, (2) the time when the operator first begins to move, (3) the time when the operator is struck-by an object, (4) name of the object that struck the operator (pan, boom drum), and (5) the operator's distance from the machinery when struck-by an object. Struck-by means a collision occurs between the operator and machine or the mine wall. The data collection in this process uses captured motions, simulated scripts and collision detection by using Jack™ modeling and simulation software.

The human-machine model was setup to generate and collect data during simulations from two different work locations: cutting drum or conveyor tail (see figure 1). From these work locations, simulation scripts were programmed to rotate the machine (4.77, 9.55 and 19.1 deg/s) until it came in contact with the virtual mine wall. In addition, during the machine's simulated rotation, the captured motions of an operator were integrated into the virtual environment. This showed the operators actual movements, one of the eight escape paths from the machine, starting from a specific distance at one of the work locations.

The operators' movements were constrained to a digital human model by using captured motion data of test subjects discussed in the previous section. The operator was placed at 1, 2, and 3 foot intervals from the conveyor tail or cutting drum. Captured motions of the experienced equipment operators were replayed in Jack software in the various combinations of kneeling, squatting and standing work postures, facing orientations and escape path directions. Only escape paths 4, 5, 6 and 7 were used because they offered at least one direction that cleared the turning radius of the machine at each work location. In order to present a realistic operator response to the moving machine, researchers programmed the operator's movement to delay the start of

Table 1 – Test subject information

Subject	Age, yrs	Weight lbs	Height, ft-in	Experience, yrs		Reaction time, sec
				Mining	Machine	
1	53	215	5-8	20	10	0.22
2	37	242	5-10	10	10	0.20
3	56	190	5-11	27	27	0.23
4	51	235	5-10	20	17	0.22
5	51	260	6-0	33	20	0.22
6	59	165	5-7	34	15	0.24
7	47	200	6-2	25	10	0.21
8	32	170	5-9	2	0.25	0.19
9	33	220	6-1	4	1	0.19
10	49	195	6-1	7	1	0.21

movement according to reaction times (Table 1) reported by Drowatzky (1981) for different age groups that ranged from 0.19 to 0.24 seconds. Also during the simulation, right and left peripheral vision views on the DHM (figure 5) and collision detection helped investigators to track whether the operator could detect movement in the machine that could stimulate a reaction.

Table 2 - Frequency and cross-tabulation struck-by summary

Work location	Tail	Drum				
% struck-by	76.8	67				
Work Location – Distance[1]	D-1[1]	T-2[1]	D-2[1]	T-1[1]	T-3[1]	D-3[1]
% struck-by	87.1	87.1	86.1	82.8	71.7	66.1
Speed, deg/s	19.1	9.55	4.77			
% struck-by	89.9	73	71.7			
Speed-rotation[2]	19 CCW	19 CW	9 CCW	9 CW	4 CCW	4 CW
% struck-by	91.1	88.9	81.7	64.5	59.6	50.1
Time[3] (s)	0.1	0.5	1	2	3	4
Cumulative[4] %	24.6	69.9	85.4	96.4	97.5	99.7
Body part	Arms	Head	Legs	Feet		
% struck-by of total[5]	61.4	23.8	11.4	3.4		

[1]Distance from work locations (**T**ail T-1,3 and **D**rum d-1,3) in feet
[2] CW = clockwise; CCW = counterclockwise
[3]Time intervals during machine rotation
[4]Cumulative percent of total struck-by events
[5]Percent of total struck-by events

The initial simulation database contained 19,440 cases that were collected from ten virtual subjects where a number of cases involved instantaneous contact information such as collisions occurring at time zero. This happened in the simulation if the operator was already in contact with the machine before it moved or at the instant it began to move. Therefore, the resulting database for analysis comprised of 14,308 cases depicting 1,296 possible test scenarios involving machine speeds and direction of rotations, work postures and facing orientations, work locations and distances from the machine, and escape paths.

Variables

Several independent variables were investigated including the machine speed, operator's distance away from the machine, operator's work posture and facing orientation, operator's work location and escape path direction. Dependent variables included time of a collision event, part of the body contacted and part of the machine contacted.

Survival Analysis Model

A Cox regression model was used to examine the influence of the independent variables on the time to contact. Cases where no contact was made were treated as censored observations. The main effects and all two way interactions were analyzed using a likelihood ratio stepwise technique. Proportional hazard checks were performed at all stages of the analysis. Type I error was set at 0.05.

RESULTS

Frequency and Cross-tabulation

Frequency and cross-tabulation analyses considered 14,308 simulations. Of the simulations examined, 10,254 exhibited struck-by events between the operator and the continuous miner equipment. A table of struck-by events for some of the factors was compiled in Table 2, for example, the operator was struck 76.8% of the time when working at the tail location. The table also includes cross-tabulations, for instance, the operator was struck 91.1% of the time when the machine moved counterclockwise at a speed of 19.1 deg/s. The cumulative percent of total struck-by events per time while the machine moved and percent of the total struck-by events of when a body part on the operator was most frequently contacted are other information in the table. The two major factors that cross tabulations showed to have an effect on the operator's ability to avoid being struck by the machine were the operators distance from the machine and the speed of the machine. The effect of the operators distance can be seen in figure 6. The differences in incident rates between a distance of 1-ft and 2-ft is small but at 3-ft the incident rate is significantly reduced. Figure 7 shows the effect of machine speed on incident rates. There is an almost linear reduction in rates as machine speed is reduced. There also were a greater incidents of struck by when the machine rotates counter clockwise with the operator located in the tail position which has a greater linear velocity than the drum at the same rotational speed. These results are not surprising but do indicate that recommendations on speed and operator distance from the

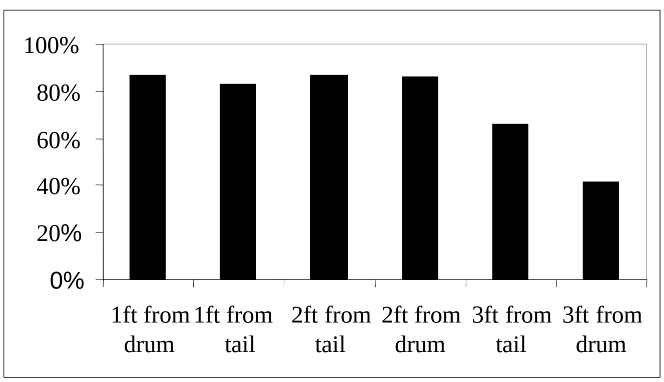

Figure 6. Percent struck vs. distance from machine.

machine could reduce operator injuries. The interaction of parameters was further explored in the survival analysis. The interaction of the parameters was quite complex with the other independent variables having an effect on the incidences of operators being struck by the machine. The difference in incidents due to the escape path of the operator is shown in figure 8. Operator posture and facing direction also affected the frequency of struck-by incidents, but appeared to have the greatest affect in combination with each other. In order to explain these interactions, a time based survival analysis was used to determine the significance of the variable interactions.

Additional data was collected from the simulations such as the parts of the body most frequently struck (figure 9) and the machine parts most frequently contacted. Upper parts of the

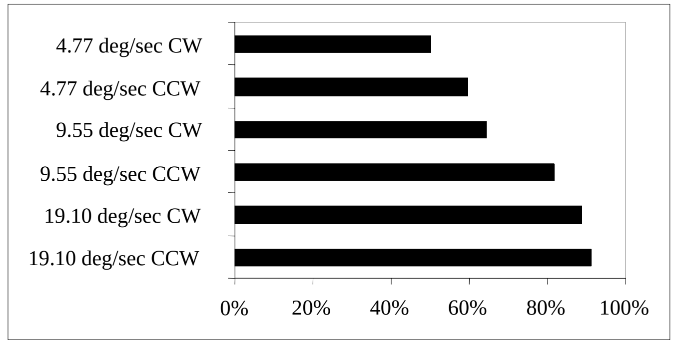

Figure 7. Percent struck vs. machine speed.

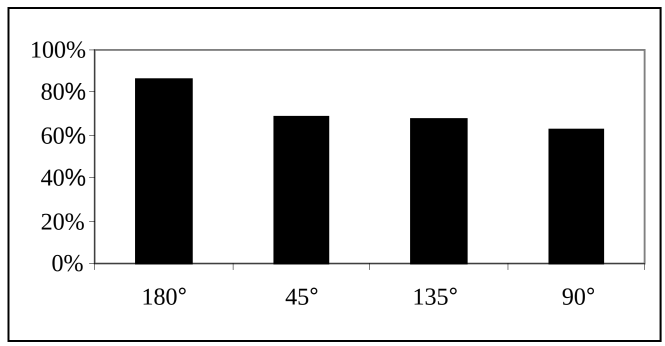

Figure 8. Percent struck vs. escape direction.

body tend to be struck most often due to the shape of mining machine particularly when at the tail which can only contact the operator's upper body. This would also explain why stature did not have a significant influence on incidents. These factors will be used in the development of work place interventions.

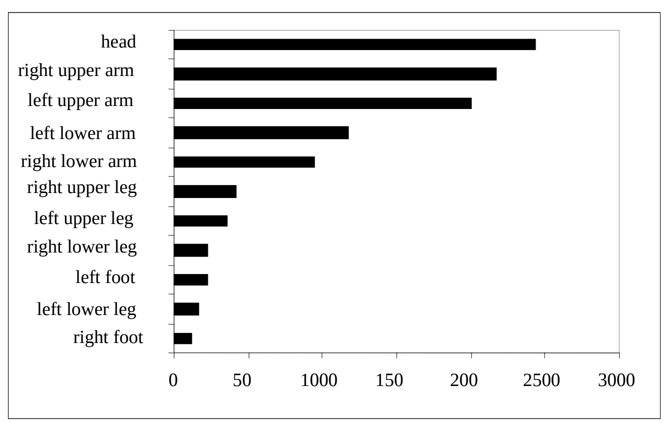

Figure 9. Body part struck.

Relative Risk

Based on the results of the Cox regression analysis, a model was developed that incorporated the main effects and interactions of the independent variables on the time to contact. All the main effects were found to be significant and

12 of 15 two-way interactions were significant, resulting in a complex risk model. In addition, the proportional hazards assumption was rejected in almost all cases, save for the machine speed variable, indicating that the hazards associated with most of these variables were changing with time. The *proportional hazards assumption* is the assumption that hazards associated with a factor are remaining relatively constant with time. For example, if a given factor halves your hazard at time 0, it also halves your hazard at time 1, or time 0.5, or at any other time during the measurement period.

Due to model complexity, analyses of relative risk were calculated while the machine was in motion at 0.1 sec, 1 sec and 3 sec. The times were chosen based on the first time recorded, the time when 98% of the cumulative incidents have occurred and a time in the middle. Using only the five lowest and the highest five relative risks calculated at these times in the simulation, Table 3, 4 and 5 were compiled and included for each time period, showing distance, speed, work posture, facing orientation, work location, escape direction and relative risk. The coefficients in this model helped to evaluate the relative risk of experiencing a struck-by event at different points during the machine movement and showed the degree of influence for each variable in the model while controlling the effects of all other covariates.

DISCUSSION

Machine speed was the most influential variable in terms of explaining the struck-by event occurring. Increases in machine speed resulted in an increased chance of being struck-by and the increased risk associated with higher speeds was constant throughout the times investigated in the study. In general, compared to the 4.77 deg/s condition (referent condition), the 9.75 deg/s speed increased risk threefold and the 19.1 deg/s condition increased risk by 8 times the referent value. The distance from the machine at the start of the test (0.1 sec), also had a significant influence. The relative risk of being struck-by the machine while working within 1-ft of the machine was the greatest at the beginning of the simulation.

Table 3 – Lowest and highest relative risk at time 0.1 seconds.

	ft	Speed deg/s	Posture	Facing	Location	Dir deg	Relative risk
Lowest	3	4.77	standing	front	Drum	45	0.0017
	3	4.77	standing	front	Drum	90	0.0023
	3	4.77	standing	front	Drum	135	0.0023
	3	4.77	standing	front	Drum	180	0.0025
	3	9.75	standing	front	Drum	45	0.005
Highest	1	19.1	standing	right	Tail	180	45.79
	1	19.1	standing	right	Tail	135	42.62
	1	19.1	standing	right	Tail	90	41.55
	1	19.1	standing	left	Tail	180	32.89
	1	9.75	squatting	right	Tail	180	30.64

Throughout the simulation the operator in a squatting work posture has a high potential threat of being struck-by. In general, this posture was associated with an increase in relative risk that was 2.5 times the standing (referent) condition. Indicating that a mid and low seam height may pose a greater probability of struck by accidents depending on posture. It seems clear that the difficulty and slow speed associated with this posture

Table 4–Lowest and highest relative risk: at time 1 second.

	ft	Speed deg/s	Posture	Facing	Location	Dir deg	Relative risk
Lowest	2	4.77	squatting	front	Drum	90	0.039
	2	4.77	squatting	left	Drum	90	0.0407
	2	4.77	squatting	right	Drum	90	0.0423
	1	4.77	squatting	front	Drum	90	0.0447
	1	4.77	squatting	left	Drum	90	0.0467
Highest	3	9.75	squatting	right	Tail	180	42.6
	3	9.75	squatting	left	Tail	180	40.97
	3	9.75	squatting	front	Tail	180	39.21
	1	9.75	squatting	right	Tail	180	30.5
	1	9.75	squatting	left	Tail	180	29.34

Table 5 – Lowest and highest relative risk: at time 3 seconds.

	ft	Speed, deg/s	Posture	Facing	Location	Dir deg	Relative risk
Lowest	2	4.77	squatting	right	Drum	90	0.0179
	2	4.77	squatting	left	Drum	90	0.0195
	1	4.77	kneeling	right	Tail	45	0.021
	1	4.77	kneeling	right	Tail	135	0.021
	1	4.77	squatting	right	Drum	90	0.0212
Highest	3	19.1	squatting	front	Tail	180	292.87
	3	9.75	squatting	front	Tail	180	291.18
	3	19.1	squatting	left	Tail	180	267.07
	3	9.75	squatting	left	Tail	180	265.53
	3	19.1	squatting	right	Tail	180	245.81

increased the time it took to escape. On the other hand, the kneeling posture was found to be the lowest in terms of relative risk of all the postures. This posture may have positioned the body in a manner relative to the machine to avoid being struck by the machine, and still allowed for a relatively quick escape via crawling. At the beginning of the simulation, front-facing orientation revealed a higher relative risk, which appeared to be due to the propensity of subjects to turn around before moving away from the machine. The extra time associated with this maneuver may result in subjects being unable to successfully avoid contact with the continuous miner. At later phases of the simulation, right-facing orientation becomes a lower relative risk.

The tail location is the highest relative risk compared to the drum location throughout the simulations. This would be explained in part by the tail being further from the axis of rotation than the drum, meaning it has a higher linear velocity.

Due to the nature of the simulation, data was not collected with an operator positioned at the center point of the machine. An operator standing in that position would have no struck by incidents in the model. Unfortunately, the rotation of the machine around it's center point makes many think it would not lead to a risk of struck by accidents when the operator was so positioned. However, tramming while positioned within the turning radius of the continuous miner can be fatal according to MSHA data (Dransite J and Huntley C., 2005). The center of the machine is no way a safe location for the operator to be positioned, because of distance from the machine and pinch points (MSHA 2006) such as if the machine slips toward the operator while tramming. The data presented here suggest that greater risk is present when the operator is positioned by the tailpiece compared to the drum (in terms of struck by accidents). However, positioning near the drum may have other consequences associated with it that may need to be considered. Relative risk of being struck-by the machine using the escape path direction 180° (path number 7) was the greatest throughout the simulation. It is clear that successful escape is less likely when moving parallel to the machine than when the escape vector has a component of motion that is away from the machine.

In summary, the data obtained in this study revealed a complex interaction of factors that affect the risk of struck by accidents when tramming continuous miners in an underground mining environment. However, the increased understanding of these relationships should ultimately result in recommendations that reduce this risk of these potentially fatal accidents in continuous miner operators. The results can also be used to set parameters for new proximity warning systems being developed, Ruff (2007), for mining equipment.

Acknowledgments

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