Using Ergonomics to Enhance Safe Production at a Surface Coal Mine — A Case Study with Powder Crews

Job tasks that involve exposure to work-related musculoskeletal disorder (WMSD) risk factors may impact both the risk of injury and production downtime. Common WMSD risks factors associated with mining tasks include forceful exertions, awkward postures, repetitive motion, jolting and jarring, forceful gripping, contact stress, and whole body and segmental vibration. Mining environments that expose workers to temperature/humidity extremes, windy conditions, and slippery and uneven walking surfaces also contribute to injury risk. National Institute for Occupational Safety and Health (NIOSH) researchers worked with powder crew members from the Bridger Coal Company to identify and rank routine work tasks based on perceived exposure to WMSD risk factors. This article presents the process followed to identify tasks that workers believed involved the greatest exposure to risk factors and discusses risk reduction strategies. Specifically, the proposed prill truck design changes addressed cab ingress/egress, loading blast holes, and access to the upper deck of the prill truck.

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INTRODUCTION

From January 2001 to January 2005, personnel from NIOSH and Bridger Coal Company collaborated on a process to implement ergonomics as an element of the safety and health program at the Jim Bridger Mine, a surface coal mine located in southwest Wyoming. In general, the collaboration involved two approaches. For the first approach, Bridger, with support from NIOSH researchers, implemented a proactive process to identify and reduce WMSD risk factors before the risk factors resulted in discomfort and pain. This process has been described elsewhere.(1–3) As part of the process, a training program was developed and implemented by NIOSH and Bridger to impart skills within the Bridger work force that would help them identify WMSD risk factors associated with their work tasks. As part of this training, an interactive exercise was designed to present work scenarios, identify plausible WMSD risk factors, and explore options (e.g., engineering controls, work procedures) to reduce the frequency, level, or duration of risk factors.

For the second approach, NIOSH, with support from Bridger employees, analyzed work tasks performed at the Jim Bridger Mine to identify and study equipment design interventions that could reduce exposures to WMSD risk factors. This article discusses the results of NIOSH's work with the powder crews.

Powder Crews and Work Tasks

At the Jim Bridger Mine, two powder crews (six members each) worked 12-hr shifts, 7 a.m. to 7 p.m., on a straight 4-day rotation (4 days on, 4 days off). Table I provides age and experience data collected for the powder crews. The general functions

TABLE I. Demographic Information for Powder Crew Members

	Age	Years Mining Experience	Years on Powder Crew
Average	41.6	14.4	12.8
Std Dev	9.4	8.7	9.1
Min	24	1	1
Max	51	25	25

Note: Powder crew members (N = 11); one position vacant.

of the powder crews were to use explosives to break up overburden and parting, which could then be removed by draglines and dozers to expose coal seams, and to break up coal seams so that the coal could be loaded into haul trucks. Information obtained from mine management and the safety department indicated that powder crews performed tasks that were physically demanding, particularly when they were exposed to extremes in weather conditions. A general outline of powder crew tasks is shown in Table II. Work duties were rotated among crew members within each crew.

Crew productivity was assessed using the number and depth of blast holes loaded and shot from January 2001 through August 2002. The three types of holes loaded and shot included:

1. *Overburden*. Mean depth was 26.2 m with a mean of 835 holes loaded and shot per month.
2. *Parting*. Mean depth was 11.5 m with a mean of 1552 holes loaded and shot per month.
3. *Coal*. Mean depth was 3.4 m with a mean of 3983 holes loaded and shot per month.

The monthly range of work completed (total depth of holes loaded and shot) was quite large—from 21,204 to 90,640 m per month. The monthly mean was 48,036 m loaded.

Tools, Equipment, and Materials Used by the Powder Crews

Powder crews were assigned four prill trucks and three powder trucks. The prill trucks were used to transport ammonium nitrate prills, fuel oil, and emulsion to the blasting site and then to mix and load the holes with a blend of these materials. These trucks varied appreciably in age, physical features, and performance, which influenced how the crew interfaced with the operating controls for driving the truck and dispensing the explosive fuel oil mixture.

Powder trucks were four-wheel drive pickup trucks equipped with crew cabs, and all three trucks were very similar in design and operation. Powder trucks were used to transport the blasting components (e.g., detonating cord, primers, and delays) from the magazines to the blasting site and to transport crew members.

Blasting components were stored in several magazines at two locations on mine property. The components were typically packaged in boxes weighing from 30 to 60 lbs. Deliveries occurred about once per week, and crew members assisted the vendor in off-loading components. Ammonium nitrate prills and emulsion were stored in silos that were similar in design.

METHODS

NIOSH personnel observed members of both crews and had numerous informal conversations with crew members to determine the scope of their duties and derive a sequential listing of work tasks (Table II). From this listing, 16 discrete tasks were identified that involved potential exposures to WMSD risk factors.

The method used to select tasks for possible redesign was based on a process that maximized employee involvement through individual and group discussions with both powder crews. These crews were quite experienced and had excellent knowledge of their job tasks. NIOSH believed that involving the crews would result in more direct use of their knowledge and skills and build ownership of potential design changes.

Individual Rating of Work Tasks

To obtain individual ratings, NIOSH personnel interviewed each crew member. The crew members were asked to rate each of the 16 tasks using a five-point scale, with 1 being "very easy," and 5 being "very difficult." When numerically rating each task, the crew members were asked to think in terms of their exposure to WMSD risk factors (based on ergonomics and risk factor awareness training). For example, what tasks required the greatest physical effort, extreme postures, and/or many repetitions of the same movements. Crew members were also asked to comment qualitatively on the tasks—what did they dislike about doing a specific task. The mean individual ratings and the number of negative comments about a task were summed to obtain a combined score for that task.

Group Rankings of Work Tasks

A series of short meetings with each of the two powder crews provided an opportunity to present and discuss the results of the individual ratings. During the meetings, each crew was asked to rank the top six individually rated tasks in order based on exposure to WMSD risk factors, with 1 being the most difficult task and 6 being the least difficult task.

Crew Interviews — Prill Truck Designs

A final meeting was held with each powder crew to discuss features of all four prill trucks. This session allowed individuals and the group to comment and discuss preferences concerning operator interface, such as the design of steps and

TABLE II. General Workflow for Shooting Overburden, Parting, and Coal

Tasks	Comments
Prepare assignments	A planning task for determining and coordinating crew member responsibilities.
Pick-up components	Lead blaster gets components from the magazines. Inventory management.
Inspect prill truck	Crew members check out and, if okay, drive one or more prill trucks to site. Crew adds ammonium nitrate prills, fuel oil, and emulsion as necessary.
Survey site	Crew members examine site prior to loading holes.
Tape holes	Crew members check to see if hole depths match up with the specifications for a given work area and to determine the presence of water in the drill holes. De-water as necessary.
Stem bottom of holes with shovel or skidder	Amount is dependent on results of taping holes. Actual hole depth should match depth of the specific blasting plan.
Prime holes	Dependent on the specific blasting plan
Load holes	Use prill trucks – calculate and dispense specific amount of ANFO (ammonium nitrate and fuel oil) and/or ANFO emulsion blend to each hole in the pattern.
Tape holes to check ANFO column for each overburden and parting hole	Prill truck operators perform this task – exit truck, measure overburden or parting hole, add ANFO or blended product as necessary.
Stem top of holes with shovel or skidder	Dependent on the specific blasting plan
Examine loaded pattern – prepare for shot	Determine blast area and set cones.
Tie off holes	Dependent on the specific blasting plan
Insert delays	Dependent on the specific blasting plan
Check tied off pattern	Communicate among crew members while walking pattern.
Position crew members	Strategic locations are chosen to prevent others from entering area.
Prepare to shoot	Follow established communication protocol.
Shoot pattern	Following communication and warning protocols
Check shot for misfires	Lead blaster, crew members
All clear communication	Lead blaster

handholds, the ladder, and other features involving seating and control layout.

Physical Measurements and Videotaping of Tasks

Physical measurements were obtained for each of the prill trucks to determine differences among the trucks and to identify designs that likely exacerbated exposure to WMSD risk factors. Video recordings of tasks were taken to identify postures associated with getting in and out of the truck cab, use of the ladder, and loading coal holes. The measurements and observations allowed NIOSH to describe the variability in truck design and to identify potential negative or positive consequences of this variability.

RESULTS

Rating and Ranking of Work Tasks

Individual Ratings

The results of the individual numerical rating appear in Table III. The range of the mean ratings was from 1.5 to 2.9. In general, these numerical ratings were relatively low when compared with the maximum possible score of 5. Overall, combined scores, derived by adding the mean numerical rating with the number of negative comments about the task, ranged from 2.1 to 12.9. Six tasks received a combined score of 9 or greater. Five of these six tasks were routine tasks performed for every drilling and blasting pattern. NIOSH ranked these six tasks as the first priority for a more in-depth discussion with each powder crew.

Group Rankings of Work Tasks

Table IV summarizes the results of the crew discussions. Both crews' rankings were very similar. Two of the tasks were ranked the same by both crews, while the other four tasks were within one ranking of the other crew.

The highest-ranked task, tying off coal holes, was discussed with each crew. To perform this task, crew members repeatedly stooped to tie off the shot at each blast hole. Discussions with the crews implied that this task did not lend itself to an engineering solution that could reduce the frequency, level, or duration of the primary risk factor (awkward postures). Therefore, this task was often performed by all crew members. This administrative control served to reduce the frequency, level, and duration of exposure for any one crew member.

TABLE III. Rating of Tasks by Individual Powder Crew Members (N = 11)

Task	Mean Rating	Number of Negative Comments	Combined Score	Priority Ranking
Stemming bottom of holes	2.9	10	12.9	1
Off-loading and stacking supplies in the magazine from the delivery truck	2.9	8	10.9	1
Climbing in and out of the prill truck cab	2.5	8	10.5	1
Climbing up and down the ladder to fill the prill truck	2.4	8	10.4	1
Tying off holes	2.4	7	9.4	1
Driving prill truck while loading holes	2.2	7	9.2	1
Filling the prill truck with ammonium nitrate prills	1.9	5	6.9	2
Taping holes	2.1	3	5.1	2
Chocking truck wheels	2.1	3	5.1	2
Stemming top of holes	2.1	2	4.1	2
Priming holes	2.0	2	4.0	2
Driving the prill truck to the site	1.6	2	3.6	3
Pre-shift inspection of prill truck	1.6	2	3.6	3
Loading holes with ANFO	1.7	1	2.7	3
Driving supply (explosives) truck to site	1.5	1	2.5	3
Loading supply truck	2.1	0	2.1	3

From the individual ratings and group rankings (Tables III and IV), three of the six tasks with the greatest exposure to risk factors involved the use of the prill trucks. Because the designs (and variability in design) of the prill trucks were suspected as contributing to the difficulty of these tasks, the prill trucks were selected as the subject for design interventions.

TABLE IV. Group Ranking of Top Six Tasks According to Exposure to WMSD Risk Factors

Task	Crew A Ranking	Crew B Ranking	Average Ranking
Tying off (coal) holes	1	1	1
Driving prill truck while loading (coal) holes	2	3	2.5
Stemming bottom of overburden holes	3	2	2.5
Climbing in and out of the prill truck cab	4	4	4
Climbing up and down the ladder to fill the prill truck	5	6	5.5
Off-loading the delivery truck and stacking components in the magazines	6	5	5.5

Description of Top Ranked Work Tasks

Loading Blast Holes

To complete this task, the operator must align the auger, which delivers a pre-set amount of explosive mixture, directly above the blast hole. Because the auger is located on the left rear of the prill truck, the operators have to twist and look over their left shoulder each time a blast hole is loaded. For each hole, the operator twisted twice to look over the left shoulder. The first time was to spot the auger over the hole; the second time was to make sure the ANFO was completely dispensed before moving onto the next hole. Side-view mirrors were not useful in accurately spotting the auger over the holes.

Meanwhile, the controls for delivering the explosive mixture were located in the cab, behind the operator, to the right of the driver's seat. Because the locations of the auger and the positioning controls were behind the operator, this task resulted in exposures to extreme awkward postures.

Considering all three types of blast holes, this short duration (twisting and reaching) task was done an average of 12,740 times per month (6370 holes loaded per month). The awkward twisting posture averaged 1062 times per month per crew member. Coal holes were more difficult to spot accurately due to the relatively small diameter hole, which took a few seconds longer. The monthly average was 3983 holes, or 664 awkward postures per month per crew member.

Climbing In and Out of the Cab

Throughout the shift, crew members needed to climb in and out of the prill truck cab to complete work tasks. Entering and exiting the cab was done most frequently when the crew members loaded overburden and parting holes and while placing additional blasting components into the holes. These tasks could not be completed from inside the cab, since the level of the ANFO column had to be measured to ensure the correct amount was loaded into each hole.

The crews estimated they climbed in and out of the cab from 10 to 90 times per day, with 30 being the daily average. The physical exertion required to climb in and out of the cab was not measured but likely contributed to the overall difficulty of this task. The design of the prill truck steps and handholds, which varied among the trucks, also increased the overall difficulty of this task. Problematic design features specific to one or more of the prill trucks included (1) the first step was too high; (2) handholds were not located within easy reach, or too few handholds resulted in operators using the steering wheel as a handhold; and (3) the steps were fairly narrow, which did not allow for secure footing when entering or exiting the cab. In effect, the design of the prill trucks increased the level of physical exertion and resulted in the use of awkward postures in performing this short-duration but frequent task.

Climbing Up and Down the Ladder

To fill the trucks with ammonium nitrate and emulsion, the driver climbed the ladder located at the back of the truck to open and close the covers and fill the bins. When climbing up and down the ladder, the crew members faced toward the truck. The risk factor exposure associated with this task was the physical exertion required to climb up and down, as well as the ability to maintain balance while climbing. Specific design features that added difficulty or risk factor exposures in performing this task included (1) the angle of the ladders, (2) location and spacing of the handrails, (3) a high first step from the ground to the platform supporting the ladder, and (4) the transition from the top of the ladder to the upper work deck.

Prill Truck Design Issues

Crew Interviews Regarding Prill Truck Designs

Table V summarizes the results of the crew meetings. As expected, all of the trucks had some negative design features as assessed by crew members. Prill Truck D, which was the newest truck, was considered the best (far better ride and comfort) of the four prill trucks. Of note, Truck D also had a few negative comments, and some features on the older trucks (e.g., the ladder design on the Truck B) were rated a superior design in comparison with the newer Truck D.

Physical Measurements

The trucks varied significantly in the design features used to drive the vehicle, dispense the explosive fuel oil mixture, enter or exit the cab, and gain access to the storage tanks. These design differences required operators to adopt different postures when (1) climbing into or out of the cab, (2) ascending or descending the access ladder to storage tanks, and (3) locating (spotting) the auger over the hole (target) to be loaded. Table VI provides measurements affecting cab ingress and egress and ladder use.

Proposed Design Changes

NIOSH proposed three design changes for the prill trucks used at the Jim Bridger Mine. A summary of the proposed interventions is provided in Table VII. The anticipated benefits of the proposed interventions included reduced risk for slips and falls, decreased physical exertion, reduced number of awkward postures, and improved ease of use.

DISCUSSION

In this case study with the Bridger powder crews, employee participation was critical, as the proposed prill truck interventions involved not only the equipment and tools used but also how the crews used the tools and equipment to perform the tasks. Participatory ergonomics, promoted by NIOSH as a significant element in successful ergonomic processes, can take several different approaches, ranging from individual employee input to membership on formal companywide committees.[4] In many cases of participatory ergonomics, employee involvement has been at the committee and workgroup level. While the ergonomic process implemented at Bridger followed this model, participatory ergonomics was taken a step further in determining interventions for the powder crew.

The powder crew members were involved in many steps of the process followed to select appropriate interventions. Employees (1) identified tasks that involved exposure to WMSD risk factors, (2) ranked these tasks based on perceived level of risk factor exposure, and (3) identified critical design features that impacted the risk associated with performing these tasks. The main advantage of following this approach was to enhance the acceptance level of interventions. The success of ergonomic interventions often is determined not by the efficacy of the design alone but also by the acceptance and proper use of the interventions by employees. In this case, every member of both powder crews had multiple opportunities to provide input.

Involving employees can also provide access to a wealth of information about the work tasks and equipment, particularly when the employees are experienced. In the case of the powder crews, the average work experience on the powder crew was 13 years. Employees provide a perspective that may be missed if they are not involved in the process.

Individual employee participation at multiple steps also has a few disadvantages. First, this approach is workable only when the number of employees affected by the intervention is

TABLE V. Crew Discussions Regarding Positive and Negative Features of the Prill Trucks

Prill Truck	Ingress/Egress	Ladder	Loading Coal Holes	Control Location	Mirrors	Seats
A Year of mfr. 1992	+ Steps are even, good location of handholds, steering wheel is easily accessible	– – Vertical climb, easy to hit your butt when you climb or descend	– Longest truck, more difficult to maneuver, PTO control outside, auger switch and computer controls are in a difficult position	– "T" handle controls are opposite in different trucks + good "T" handle design	– Concave mirrors too small	– Cab not roomy enough + Ride comfortable
B Year of mfr. 1999	– Too high to climb	+ Once you get to the bumper, it is easy to climb due to the slanted ladder and good rungs and handrails	+ PTO inside, easier to run, toggle switch for throttle set control	– Button fixture, fixed position above arm	+ and – Mixed within and across the crews	– Seat belt does not move at seat, poor suspension, hard ride, rough ride when full or empty + Good ride when fully loaded
C Year of mfr. 1995	– – Steps are too narrow, poor location and narrow door	– – Vertical climb	– Reset, cannot monitor fuel% from inside + Outside auger control	– "T" handle controls are opposite in different trucks + Good "T" handle design	– Mirrors old and too small	– Poor suspension – – Not very adjustable, no adjustment for the seat back
D Year of mfr. 2002	– Would be better if it had outside handholds + Good steps and height	– Slanted ladder, but bad handrails and hook at the top (where you transition to the upper deck)	– Throttle set control not easy to use or reset, auger too short, cannot monitor fuel% from inside + Good control, outside auger control	+ Button shifter console mounted to seat, cab bigger	+ Good types of mirrors, larger and wider, broader visibility	+ Cab bigger, more comfortable, adjustable seat ++ Good suspension
Comments	Frequency of ingress and egress estimated between 10–90 times per day. An average of 30 times per day				Mirrors have improved with each new truck	

Notes: Comments were qualitatively rated by NIOSH as either a positive or negative statement. If multiple workers repeated the same comment, that comment was rated as either a double negative or double positive (+ is a positive, – a negative, – – is a double negative, and ++ a double positive). PTO = power take off.

TABLE VI. Prill Truck Measurements Relevant to Cab Ingress/Egress and Ladder Use

Task	Truck Feature	Prill Truck A	Prill Truck B	Prill Truck C	Prill Truck D
Climbing in and out of truck cab	Size of steps	129.5 × 10.2	83.8 × 12.7	100.3 × 11.4	91.4× 12.1
	Location of steps relative to truck door	63.5 cm to right of door	20.3 cm to right of door	61.0 cm to right of door	27.9 cm to right of door (top) 33.0 cm to right of door (bottom)
	Distance from ground to first step	50.8	55.9	44.5	42.5
	Distance from first step to second step	43.8	45.7	43.2	48.9
	Distance from second step to floor of truck	43.2	45.7	35.6	34.9
	Offset between steps	2.5	6.4	2.5	7.6
Climbing ladder	Angle of ladder	82°	68°	90°	75°
	Distance from ground to first step/rung	43.2	63.5	34.3	62.2
	Distance between first and second steps/rungs	28.6	57.2	36.8	31.8

Note: All measurements are in centimeters unless labeled otherwise.

limited. As the number of employees increases for a particular work activity, the amount of data gathered and processed could become unmanageable without applying more sophisticated statistical methods. Another disadvantage is the amount of time required to collect and process the input received from the employees. Obtaining employee input added several steps to the process, and because of rotating work schedules, additional visits to the mine site were needed to coincide with specific crews being on duty and accessible to participate in the interviews and meetings.

Using prill trucks to load blasting holes was considered by the powder crews to be far superior to hand loading. However, the prill trucks, as designed, resulted in exposures to WMSD risk factors. Obviously, some risk will always be present. New equipment and tools often reduce risk but can bring a different set of problems and exposures.

To prevent unnecessary risk, changes in equipment design should be tested to see if they reduce risk, add new risk, or complicate the work process. One method for testing design changes is to incorporate the changes into one truck, thus

TABLE VII. Proposed Prill Truck Design Interventions

Proposed Intervention	Design Considerations	Anticipated Benefits
Redesign the ladders used to access the top of the prill truck	Tread type, size and spacing, handrail design, mounting and dismounting, and vertical angle	Reduced slip and fall risk, and improved ease of use
Redesign handholds for getting in and out of cab	Location and size	Reduced slip and fall risk, decreased shoulder and arm exertion, and improved operator comfort
Redesign steps for getting in and out of the cab	Location, size, and type of tread	Reduced slip and fall risk and reduced exertion
Use remote camera for verifying the alignment of the prill boom and spout	Complexity, ease of use, and utility	Reduced twisting of the neck, upper torso, and back

providing an opportunity to further refine the redesigns and gather additional input from the crew members. When new trucks are bought or when trucks are modified in-house, the design changes suggested during this study should be considered for reducing the level, duration, and frequency of exposures to key WMSD risk factors. These design changes could likely reduce the risk of developing a musculoskeletal disorder, as well as help to prevent acute injuries such as those that may result from a slip or fall.

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