

Ergonomics of abrasive blasting: A comparison of high pressure water and steel shot

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Abstract

Abrasive blasting with silica sand has long been associated with silicosis. Alternatives to sand are being used increasingly. While NIOSH has done extensive investigations of the respiratory effects of the substitutes for sand, the ergonomic effects of the substitutes have not been examined. Too often, hazards are shifted, and technologies that might save workers' lungs could do so at the expense of their musculoskeletal systems. Hence, the objective of this study was to examine the ergonomic effects of alternatives to sand. Multiple methods, both qualitative and quantitative, were used to yield numerous kinds of data for the analysis of exposures to abrasive blasters. PATH, a method for quantifying ergonomic exposure in non-routine work, was combined with interviews with workers, biomechanical modeling and noise level readings to assess the ergonomics of two abrasive blasting operations: high-pressure water and steel shot. Advantages and disadvantages of each medium are discussed. High-pressure water was slightly less ergonomically stressful, environmentally cleaner, much quieter and less dusty than steel shot, and it was reported to be slower on those tasks where both media could be used.

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1. Introduction

Abrasive blasting with silica sand has long been associated with silicosis. Alternatives to sand are being used increasingly. While NIOSH has done extensive investigations of the respiratory effects of the substitutes for sand, (Porter et al., 2002; NIOSH, 1998) there has been no research about the ergonomic effects of the substitutes. Too often, hazards are shifted, and technologies that might save workers' lungs could do so at the expense of their musculoskeletal systems; hence the objective of this study is to examine the ergonomic effects of alternatives to sand, and to evaluate the factors that might influence the adoption of these technologies. Multiple methods, both qualitative and quantitative, were used to yield numerous

kinds of data for the analysis of exposures to abrasive blasters. This study does not link those exposures to outcome data.

Construction work presents several challenges to occupational health research, mainly because of the non-routine nature of the work. PATH (posture, activities, tools and handling), a work sampling-based approach, was developed at the Construction Occupational Health Project at UMass Lowell in early 1990s to characterize ergonomic hazards in the construction industry (Buchholz et al., 1996). Long periods of observational sampling are needed to accurately determine the exposure to non-neutral postures in construction work (Paquet et al., 2001). PATH allows quantified estimates of non-cyclical or non-routine work to be made by taking a "postural snapshot" at regular intervals over many hours (Buchholz et al., 1996). The PATH protocol has been used to evaluate ergonomic exposures in several construction trades (Buchholz et al., 1996; Punnett and Paquet, 1996; Paquet et al., 1996, 2001)

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as well as in non-construction sectors (Pan et al., 1999; Rockefeller, 2002). One of the weaknesses of the PATH method is the difficulty in quantifying the duration of static postures. In this study, we chose to use the PATH method because abrasive blasting is neither cyclical nor routinized. PATH analysis was combined with interviews with workers, biomechanical modeling and noise level readings to assess the ergonomics of two abrasive blasting operations: high-pressure water and steel shot. These two abrasive blasting methods were analyzed because they are very common in the region. They are both used to remove paint from steel structures, like bridges, and hydroblasting is also used to scarify concrete, usually road surfaces.

2. Methods

2.1. Observation—interviews

A total of 15 abrasive blasters were interviewed. All workers had used both steel shot and water and all but one, who was a Laborer, were members of International Brotherhood of Painters and Allied Trades (IBPAT). A member of IBPAT introduced us to the blasters using steel shot on site. We introduced ourselves to the hydroblasters with the imprimatur of the union, so the comfort level and likelihood of honest responses was high. Workers were asked a series of open-ended questions covering the efficacy of abrasives, their preferences from both comfort/health and efficacy standpoints, and a health survey. Interviews were private; they took place either in a corner of the worksite, or a coffee shop after work, and lasted between 30 and 45 min.

2.2. Observation—PATH

Two observers watched four different operations: painters using steel shot to remove lead paint from a bridge (6 occasions); a Laborer using hydroblasting to recondition concrete on road surfaces on a highway (observed on two separate contracts); painters using hydroblasting to remove temporary surface preparation, or lead paint, from steel columns (2 occasions); and painters hydroblasting to remove paint from a steel supported viaduct (2 occasions). The observations did not include set up or clean up activities.

The observers used hand-held computers (Compaq Aero 1500, Casio E200, and Toshiba e310) to record PATH observations. The PATH template was programmed onto the PDA using PenFact, Inc's InspectWrite software. The PATH template included tool and task-related variables from prior observation. Posture codes were derived from the Ovako Work Posture Analysing System (Karhu et al., 1977).

Site observations were made on four construction sites in Boston: the Tobin Bridge, the I90–I93 interchange, the Leonard Zakim Bunker Hill Bridge, and the I93N tunnel. Discrete observations were made every 90 s. The raters

were trained in PATH analysis. Inter-rater reliability was determined to be 80% or better for the postural variables, and the task variables had very low variability.

The PATH method requires field measurement of tool weights, materials, equipment dimensions and specifications. In this study, these data were obtained, as part of tool specifications, from industry sources.

2.3. Biomechanical model

A biomechanical model was used to estimate the forces on a worker's body during the tool operation. The biomechanical wrist model considered both the external and internal factors such as the weight, shape and position of the blasting tools, the drag force of the high-pressure water and steel shot, and the wrist postures.

It utilized two-dimensional free body diagrams and analyzed the forces and moments in two steps. The forces exerted on the two abrasive blasting tools (Appendix: Figs. 1 and 2) were analyzed based on the assumption that the tools were held horizontally to work on a vertical surface in front of the operator. The effects of different angles of operation with various levels of water pressure were considered within the hydroblasting method to model hand forces under a sample of conditions observed on site.

To assess the biomechanics, a hypothetical, right-handed 50th percentile US male, with a height of 1.77 m (69.7 in) and a weight of 75.1 kg (165.6 lbs) (University of Michigan, 1999) operator was modeled. A two-dimensional free body diagram was drawn to analyze the forces and moments at the wrists for the subject using each tool (Appendix: Fig. 3). Because the model was two-dimensional only, the radial-ulnar plane of motion for the wrist was considered.

2.4. Noise measurement

Additionally, noise measurements were taken using a Quest sound level meter, Model 2800 and calibrated with the Model QC 10 calibrator. Sampling was done for 60-s periods, with the decibel level averaged over each period. Because of accessibility, 5 readings were taken approximately 1.83 m (6 feet) from the steel shot blasting surface, and 5 readings were taken 6.10 m (20 feet) from the water blasted surface. With steel shot blasting, the noise level was constant, because, as described below, the nozzles were taped to be constantly "on." Hydroblasters controlled the trigger, so their noise level was off and on. Noise readings were taken only when blasting was occurring.

3. Results

3.1. Observations—interviews with blasters

The surveys covered a range of topics, including pros and cons of blasting methods, health effects and other concerns of workers. We have included those results that are pertinent to ergonomics and worker health.

A striking finding, noted through both observation and interviews, concerned the nozzles used with steel shot. The nozzles are badly designed and prompt workers to engage in unsafe coping strategies. Steel shot nozzles require that a lever be depressed to operate; the lever is parallel to the length of the nozzle and is squeezed, much like one would squeeze a small stapler. It is designed this way for safety reasons. If the hose is dropped it would shut off, and thereby prevent the stream of steel shot from blasting a worker. However, because it is so uncomfortable to squeeze the lever for more than a few minutes, workers tape the lever down, in “open” position, with duct tape. Although this arrangement no doubt is better for their wrists and hands, it presents a serious safety hazard because the “dead man’s switch” is overridden. This nozzle is ripe for re-design.

Steel shot is very dusty. The blasted material turns to dust, as does the recycled steel grit, which turns to powder after many uses. Visibility was limited to about 6.10 m (20 feet) in the containment area where steel shot was used. This made the research observations difficult, yet blasters did not complain about lack of visibility from the dust—only that the grit scratched the plastic facemasks and thereby limited their vision.

Steel shot “cuts” faster than water. It cleans the surface very well, produces a good profile for painting (which water can’t do, it can only clean) and it is recyclable. Blasting lead paint with steel shot requires a shower station (OSHA standard 29 CFR 1926.62 (i)(3)(i)). Blasters using steel shot wear a hood with supplied fresh air. The hood allows workers to regulate the temperature of their air, so they are comfortable in a range of temperatures. But because protective gear is not 100% protective, workers blasting lead paint are exposed to lead. Even with hoods and showers, workers are exposed. This study did not examine blood lead levels of blasters, yet half the blasters reported being medically removed at least once a year. When a blaster from upstate NY was asked what he and his co-workers do in the winter, when it’s not blasting and painting season, he said, “Sit on the couch, drink beer, look at the snow and watch our leads go down.” (“leads” meaning, blood lead levels).

Every blaster who was using steel shot was more concerned about lead exposure than anything else about the job. This was due, at least in part, to the fact that they have regular training and medical monitoring for this hazard.

Like steel shot, hydroblasting has advantages and disadvantages. Hydroblasting greatly reduces dust exposure. This reduction of dust is particularly important when the surface being blasted contains a hazardous material, like silica (concrete, for example) or lead (lead paint). While it is possible that during hydroblasting, dust particles are aerosolized in the water droplets and could be inhaled, visible dust was nil, and the blasters themselves claim that one of the chief advantages of using water is that “there’s no dust.” There are other advantages to water.

“It’s clean, it’s mobile, There’s no lugging grit or hoses or a pot...and other trades don’t have to breathe your dust.” Although hydroblasting requires a reliable water supply, overall, water was considered less cumbersome. Environmental clean-up is easy because the slurry that is produced, in this case, of lead paint and rust, is easily vacuumed and sometimes can be funneled into a tank. The slurry is separated from the water and is disposed of as hazardous waste. The water is filtered and reused.

There are three disadvantages to water. The first is that “no matter what you do, you always get wet.” This is a big problem in cold weather, when, although the water comes out hot because of the pressure, it splashes back and can coat the blaster in a thin layer of ice. Secondly, working with water impairs the worker’s visibility, because his facemask is always wet. “You can get hurt trying to get visibility” (by rinsing the mask). Lastly, when asked about safety concerns, a couple of the blasters were concerned with electrical hazards and water, but more of them were worried about working with water under such high pressure (276 MPa, 40,000 psi). “It’s the most dangerous (of all the abrasives). It can get you without you knowing ... requires constant vigilance...The hose could blow at any time.” Another said, “Water lines do blow...you must have no fear. You’re constantly doing something that could hurt you or kill you. You go for the big money and live for the day.” Apparently some hoses are sheathed, to reduce the chance of explosion, but this was not reassuring; it merely made inspection for holes in the hoses impossible. The hydroblasters were fearful about their equipment, whereas the shot blasters were more concerned about lead exposure and being rushed at the end of the work day and not being given enough time to shower off the lead dust. They were adamant about not bringing lead home to their families.

Although one of the benefits of hydroblasting cited by blasters is the lack of dust, it is not overwhelming enough to make it the blasters’ choice. When asked which method he preferred, one blaster said, “When I get sick of the dust, I go for the water, and when I get sick of not being able to see, I want the dust.” No strong preferences were registered by any of the blasters for either blasting medium because both methods have advantages and disadvantages.

Table 1 summarizes the themes of the comments and shows how many of the 15 blasters commented on the characteristics of each medium, when asked “what are the pros and cons of each method?”

3.2. Observations—PATH

Observations were made on numerous occasions between May 2001 and November 2002. The environmental conditions ranged from sunny and hot on some days to damp and cold inside the tunnel on other days. The observation site for steel shot blasting was a steel bridge being completely reconditioned. Research observers on the bridge were required to wear full body protection and full

Table 1
Number of blasters who commented on traits of each medium

Characteristic of the medium	Steel shot	Hydroblasting
Dustiness—"it's a damn dirty job"	14	0
No dust	0	8
It's fast	5	0
It's slow	0	7
Impaired visibility	0	4
Pain—"it stings"	3	0
Discomfort—"being wet all the time"	0	7
Danger	1	7
Environmentally friendly	0	8

face masks while in the containment area which was set up to trap and reclaim dust and steel shot. The containment area consisted of floor decking and canvas tarps on the sides. The bridge supporting the underside of a highway was the ceiling. Observations in the containment area were very difficult because of poor lighting and dusty air. Also, some distance, as well as constant vigilance, had to be maintained to avoid being hit by steel shot. Observations of hydroblasting were much easier because they were on solid, well-lit surfaces and there was no dust. Table 2 shows the results of the PATH data collection, showing that the two operations have some characteristics that are similar, and some contrasting.

In Table 2, operating "with" or "without support" refers to any biomechanical advantage that the operator used while holding and operating the tool. A typical example is the operator leaning against something to support his body or the force of the hose, or resting the hose on some support, like some scaffolding, so that he would not be carrying the whole weight of the hose.

The PATH data show that blasting postures are a function of access to the blasting surface, rather than simply a function of the task or activity. The activities consist mainly of operating the tool (89% of the time in steel shot blasting and 84% in hydroblasting), which is a prolonged, static activity. In our study, the position of the shoulders during hydroblasting is different from that in steel shot because the blasting surface in the steel shot operation we studied included work above the head. The hydroblasting operations we observed were either below the feet, or straight ahead, and the elbows were always below the shoulders. Similarly, the leg postures were either neutral or lunge during hydroblasting, whereas the steel shot operation required kneeling in certain situations. Hydroblasting required frequent trunk twisting as the blaster often had to twist and blast a path to his side while walking straight ahead. The difference in the hand postures was most likely due to the fact that the hydroblasting "wand" had handles, but the steel shot nozzle did not. The shot blasters could adjust their hand positions somewhat.

In general, the steel shot operation required more variation of the posture of the body segments, due to the confined workspace inside the containment area. An interesting phenomenon with ergonomic implications is

Table 2
PATH observations on steel shot and hydroblasting operations

		Steel shot		Hydroblasting	
Number of observations		75		113	
Number observed		3		3	
Variable	Value	%	N	%	N
Trunk	Neutral	36	27	55	62
	Moderate forward flexion (20–45°)	40	30	4	4
	Severe forward flexion (>45°)	16	12	1	1
	Lateral bend (>5°)	3	2	0	0
	Lateral bend and twist	3	2	0	0
	Twist	3	2	40	45
	Bend backward (>5°)	1	1	0	0
Shoulders	Both arms down	72	55	100	113
	One elbow above shoulder	18	14	0	0
	Both elbows above shoulder	9	7	0	0
Legs	Neutral	65	49	78	88
	Kneel	15	11	1	1
	Lunge	5	4	20	23
	One knee bent (>35°)	5	4	1	1
	Squat	8	6	0	0
	Sit, legs dangling	1	1	0	0
Hand 1	Empty	1	1	8	9
	Gross grasp, operating trigger	60	45	83	94
	Gross grasp, not operating trigger	35	26	9	10
	Other	3	2	0	0
	Pinch	1	1	0	0
Hand 2	Empty	7	5	7	8
	Gross grasp, operating trigger	7	5	1	1
	Gross grasp, not operating trigger	84	63	91	103
	Other	3	2	0	0
	Pinch	0	0	1	1
Activities	Handle/operate tool with no support	53	39	4	4
	Handle/operate tool with support	36	26	80	94
	Move hose	8	6	4	5
	In between activities	1	1	12	14
	Other	1	1	0	0
Tools	Hose/nozzle	97	72	93	104
	Other	3	2	7	8
MMH	Carry	5	2	3	1
	Lift	95	39	97	37
Weight	<4.5 kg (10 lbs)	12	9	9	10
	5.0–22.7 kg (11–50 lbs)	87	65	91	98

the relatively little time observed "in between" activities, which is rest time, in the steel shot operation. The steel shot blasters' nozzles were always "on" because they were taped

that way, so unlike the hydroblasters, the steel shot blasters were less likely to turn off the stream of grit. Also, they were in a loud containment area, and were wearing a completely contained personal protective air supply that severely limited communication.

Because during PATH data collection, it was becoming clear that the posture variation we were observing was related more to the access to the surface than to the blasting medium, and because there was so much difficulty in our own access to clearly viewing the blasting activity, we decided that collecting a high number of observations would not necessarily improve the generalizability of the results as they relate to linking posture to activity. Therefore, the data should not be interpreted as representative of all blasting operations.

3.3. Biomechanical model

Table 3 summarizes the information about the two blasting tools and materials used.

After inputting the estimated values of the tool weight and the drag forces of the high-pressure water and steel shot and air (Table 3) into the static force and moment equations (Eqs. (1), (6) from Appendix) the forces at the hands were computed. According to Webb Associates and Dempster (Chaffin et al., 1999), the hand weight (W_h) and the moment arm of the hand at the wrist point (m_h) for a hypothetical subject, a right-handed 50th percentile US male, were calculated as $W_h = 0.45$ kg, $m_h = 0.09$ m. With these values and the results from the force analysis of the tools, the wrist moments could be determined (Table 5). Specifically, the hand forces during hydroblasting with different angles of operation and various pressure levels were computed to investigate the influences of reactive forces generated by the water jet (Table 4).

3.4. Noise

Steel shot was much noisier than hydroblasting. In fact, it was approximately twice as loud as hydroblasting. The A-weighted sound level was measured, and the readings were normalized to 1.83 m (6 feet) and resulted in:

$$\text{Leq (hydro)} = 106.6 \text{ dB (A)},$$

$$\text{Leq (steel)} = 109.5 \text{ dB (A)}.$$

Table 3
A summary of factors measured and assumed in the biomechanical model

Tools and materials	Hydroblasting	Steel shot blasting
Description	0.013 m (1/2") inlet, α is approximately 45°	0.011 m (7/16") venturi nozzle, made of Brass poly-tungsten
Weight (W)	7.3 kg (16 lbs) (Aqua-Dyne, Inc.)	5.0 kg (11 lbs) (Marco, Inc.)
Flow rate (Q)	6.3×10^{-4} m ³ /s (10 gpm) (water)	0.33 kg/s (43.9 lb/min) (steel shot mesh) 0.12 m ³ /s (254 ft ³ /min) (air)
Pressure (P)	69 MPa (10,000 psi) (water)	0.69 MPa (100 psi) (air)
Drag force (F)	231.3 N (52 lbs) $F(N) = 4.42 * Q \text{ (m}^3/\text{s)} * \sqrt{P \text{ (Pa)}}$	17.3 N (4 lbs) $F(N) = 0.044 * Q \text{ (kg/s)} * \sqrt{P \text{ (Pa)}}$

Normalized to 0 m (0 feet) distance (at the source) the difference remains 3 dB but the absolute numbers are higher. Hydroblasting averaged 122.7 dB (A) and steel shot averaged 125.6 dB (A). We normalized to 0 m (0 feet) to estimate worker exposure, but the distance from the noise source varied both within and between blasting media. The hydroblasting wand was at least 0.91 m (3 feet) long, so the water hit the surface anywhere from 0.91 to 2.13 m (3–7 feet) away from the worker. Similarly, the steel shot hit the wall anywhere from 0.61 to 1.52 m (2–5 feet) from the blaster. Just to put our results in perspective, the OSHA standard permits a 30 min exposure at 109 dB (A) for a full day allowable dose. The standard does not take into

Table 4
Predicted hand forces associated with select values of Q , P , γ

Q (m ³ /s)	P (MPa)	γ (deg)	F_R (N)	F_L (N)
6.3×10^{-3}	69	0	85.4	82.3
6.3×10^{-3}	69	22.5 ^a	104.5	56.0
6.3×10^{-3}	69	30	92.1	68.5
6.3×10^{-3}	69	45	101.9	67.6
6.3×10^{-3}	69	60	112.5	67.2
6.3×10^{-3}	69	75	126.3	70.3
6.3×10^{-3}	69	90	137.9	76.5
6.3×10^{-3}	276	0	214.4	183.7
6.3×10^{-3}	276	22.5 ^a	218.0	173.0
6.3×10^{-3}	276	30	221.1	170.4
6.3×10^{-3}	276	45	239.3	171.3
6.3×10^{-3}	276	60	240.2	168.1
6.3×10^{-3}	276	75	252.6	170.4
6.3×10^{-3}	276	90	264.2	176.1

^aWhen γ equals 22.5°, the directions of F and W are on the same line (vertical).

Table 5
Hand forces and wrist moments during the hydroblasting and steel shot blasting operations

Blasting operations	Hand forces (N)		Wrist moments (N * m)	
	Right	Left	Right	Left
Hydroblasting	85.4	82.3	6.4	6.1
Steel shot blasting	25.8	25.8	2.7	2.7

account hearing protection, but it is clear that the blasters have extremely high noise exposures.

Noise from steel shot blasting was constant, and the noise level of hydroblasting is punctuated by pauses. Our readings were only taken while blasting was occurring, so the difference in noise levels is actually underestimated here, because the readings in hydroblasting do not include the “quiet” times, the pauses between blasts to adjust the hoses, or to rest. As an aside, although rest periods were not measured, it should be noted that steel shot blasters did not control the flow of grit, and once they were suited up with hoods and supplied air, they usually paused only for lunch. In contrast, the hydroblasters took more frequent breaks, because their gear was less cumbersome and they controlled the flow of water, and the equipment malfunctioned occasionally.

4. Discussion

This study began with the hope of finding a definitive answer to the question, which is ergonomically more stressful to the blaster, and which method do blasters prefer, steel shot or hydroblasting? Blasters had no clear preference, and so we will discuss what each method of analysis revealed. Both our personal observations, and the PATH data, indicated that physical stress is determined both by access to the work surface, the biomechanical forces, and postural requirements of tool and material handling. Though the tasks are typically non-cyclical, or at least have long, irregular cycles, most of the blasting work involved static posture and muscle use. Operating the blasting tool was static in nature, an ergonomic risk factor that PATH did not characterize well.

The biomechanical model of this static job demand indicated that the observed hydroblasting required more reactive force against the hand than steel shot. It should be noted that the biomechanical model was not intended to estimate the actual hand forces and wrist moments during the entire tool operations. The model simulated a two-dimensional activity, with some consideration for the direction of the applied force. Therefore, the model only considered ulnar/radial wrist deviation postures. Nevertheless, in practice, the hand and wrist postures and the tool positions could always change, and, in fact were observed to change in response to different surface locations. The consistency of the results, when considering other work situations and wrist postures, needs to be investigated. Moreover, the hand forces were the combination of both the grip and hold forces at the x - and y -axes, where the two blasting techniques yielded different stresses due to different tool designs. Specifically, the steel shot tool required relatively more grip forces because it did not have a handle. The handle of the hydroblasting tool allowed reactive forces of the tool to be counteracted by normal forces directly in line with the forearm. Thus, the grip forces were only necessary to hold the hydroblasting tool in line with the counteracting normal forces of the arm, rather

than additionally supplying the counteractive forces through friction as well.

Our results were consistent with Hudock (2003) who, also using multiple analysis methods, found that the postural risks in blasting are more a factor of access to the work surface than type of blasting. However, by use of the PLIBEL analysis method, Hudock found that hydroblasting had a higher risk rating at the forearm and hand than steel shot, probably due to the poor tool-hand coupling observed in the hydroblasting. In our study, two factors differed from Hudock's study and affected the result. The hydroblasting tool-hand coupling was good, and the water pressure was much greater. So, though the overall conclusion of our biomechanical model (Appendix) was consistent with the conclusion of Hudock's PLIBEL method, a critical difference was the greater forces of the high-pressure water (Table 5) observed in this study. Table 4 gives several examples of how these forces can vary. Hence we conclude that though the hydroblasters had to react to greater force, we observed that the hydroblasting wand had better coupling, and the work observed allowed for better access to the work surface than the steel shot blasting we observed.

Interviews revealed the fear associated with hydroblasting. Hydroblasters expressed both a fear of electrocution, and fear that the hose would explode. So, while hydroblasting was quieter and much less dusty than steel shot, it was much more anxiety-provoking. The effects of this stress should not be underestimated on the health of a worker.

5. Conclusions

We have three recommendations for ergonomic improvements. Because access to the work surface is a major factor in the postural risk factors observed in this study, equipment that allows for better access ought to be considered a high priority for ergonomic intervention. A hydroblasting foreman advocated the use of lifts, explaining that they get the men closer to the blasting surface, which is efficient and keeps them from getting tired. Attaching a mount to such lifts is an idea that has been discussed before (Hudock, 2003), and the present study concurs. The lifts and the mounts would have to meet the strength capabilities of supporting a high level of static force, as can be calculated with the formulas of flow rate used in Table 3. The mount used for fire hoses on ladders is a good conceptual model. Other mounts and stand ideas could be designed to greatly reduce the static muscle requirements of the operator for operation not requiring personnel lifts.

Second, the steel shot nozzles are ripe for redesign. They are currently taped in the “on” position to prevent hand fatigue but the taping overrides the dead man's switch, which presents a serious safety hazard. The use of handles, as shown with the hydroblasting wands, would probably decrease grip force requirements.

Lastly, and this pertains only to some of the blasting operations we observed, we question the practice of painting metal. We realize that metal is painted to prevent corrosion, but a system that requires blasting and repainting every few years seems inefficient at best, and quite unhealthy at worst. The blasters realize they’ve been breathing lead dust for years, and now that lead in paint has been replaced with zinc, they are concerned about the health effects of zinc. Perhaps there is a building material that would not need this kind of maintenance, and would not be unhealthy. This is a “sustainable building” project, beyond the scope of this paper, but worth pondering because of its influence on the ergonomics of abrasive blasting.

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Appendix

The forces exerted on the two abrasive blasting tools (Figs. 1–3) were analyzed. To study the influences of the external reactive forces generated by the water jet, which are determined by both the water pressure and flow rate at the orifice, a generic biomechanical model was simulated to analyze the forces on the hydroblasting wand.

In Eq. (1), W is the hydroblasting tool weight; F is the drag force of the high-pressure water; F_{Lx} and F_{Ly} are the left hand forces, F_{Rx} and F_{Ry} are the right hand forces; M and N are the summation of those forces in the x and y axes.

$$\begin{aligned} \sum M_g = 0 &\Rightarrow F_{Lx} * a + F_{Rx} * b + F_{Ly} * c - F_{Ry} * d = 0, \\ \sum F_x = 0 &\Rightarrow F_{Lx} + F_{Rx} = M, \\ \sum F_y = 0 &\Rightarrow F_{Ly} + F_{Ry} = N. \end{aligned} \tag{1}$$

In this model, the relationships among the four moment arms are assumed as $c = 2d = 2b = 4a$, in Eq. (1).

$$\begin{aligned} 6F_{Ry} - F_{Rx} &= M + 4N, \\ 6F_{Ly} - F_{Lx} &= 2N - 2M, \\ F_{Lx} + F_{Rx} &= M, \\ F_{Ly} + F_{Ry} &= N. \end{aligned} \tag{2}$$

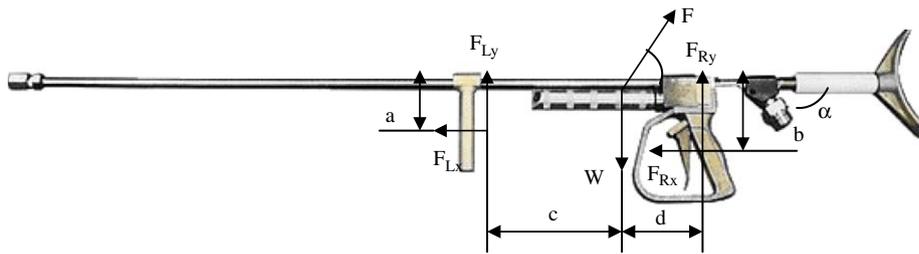


Fig. 1. Force model of a hydroblasting tool.

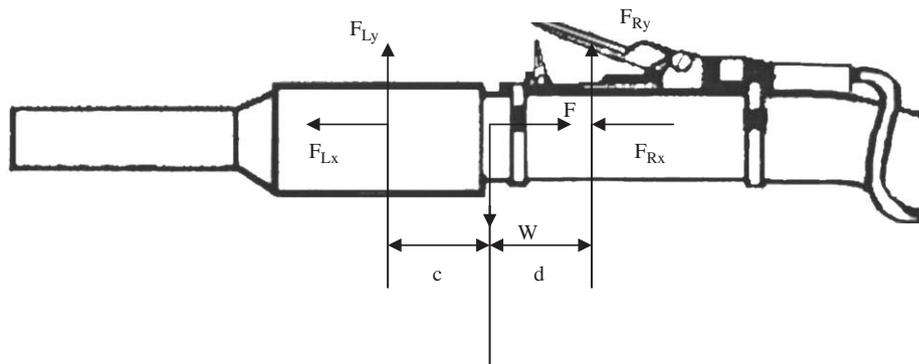


Fig. 2. Force model of a steel shot blasting tool.

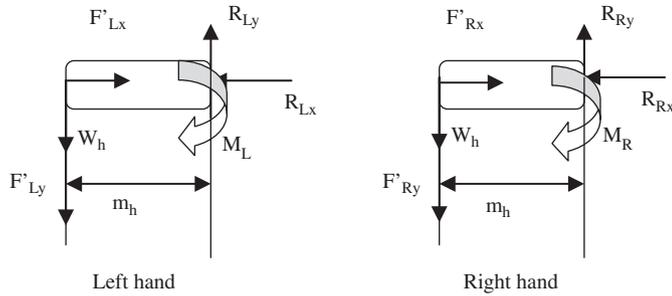


Fig. 3. Force and moment model of the left and right wrists during operation.

The optimal solutions for F_{Lx} , F_{Ly} , F_{Rx} and F_{Ry} are:

$$F_{Ry} = \frac{N(M + 4N)}{6N - M}, \quad F_{Rx} = \frac{M(M + 4N)}{6N - M},$$

$$F_{Ly} = \frac{N(2N - 2M)}{6N - M}, \quad F_{Lx} = \frac{M(2N - 2M)}{6N - M}.$$

Thus

$$F_R = \frac{M + 4N}{6N - M} \sqrt{M^2 + N^2},$$

$$F_L = \frac{2N - 2M}{6N - M} \sqrt{M^2 + N^2}. \quad (3)$$

If γ is used to denote the incline angle of the wand (the angle between the wand barrel and a horizontal line), and the relationship between α , the joint angle between the hose orifice and wand barrel, and β , the angle between the direction of F and wand barrel, is fixed as $\beta = 90^\circ - \alpha/2$, M and N can be computed as

$$M = F \cos \beta - W \sin \gamma,$$

$$N = W \cos \gamma - F \sin \beta. \quad (4)$$

Using the equation of Table 3 for equating drag force to flow rate and pressure (WJTA, 1994),

$$F(N) = 4.42 * Q \text{ (m}^3/\text{s)} * \sqrt{P \text{ (Pa)}}, \quad (5)$$

where Q represents water flow rate at the orifice, and P is water jet pressure, then different values can be assumed for computation (e.g., $W = 7.3$ kg, $\alpha = 45^\circ$, $\beta = 67.5^\circ$). With different values of Q , P , and γ , different forces required on the right and left hands could be determined. In the field, the nozzle aperture can be used to adjust the value for Q . As a basic simulation using the model, when $Q = 6.3 \times 10^{-3}$ m³/s, $P = 69$ MPa, $\gamma = 0$, M and N could be calculated as 89 (20) and -142 (-32), respectively. The forces at the right and left hands would then be 85.4 N (19.2 lbs) and 82.3 N (18.5 lbs), respectively. When the pressure (P) increases to 276 MPa (40,000 psi), and the flow rate (Q) and incline angle (γ) keep the same, the right and left hand forces were 214.4 N (48.2 lbs) and 183.7 N (41.3 lbs), respectively. Table 4 summarizes different simulation results. Given the value of 6.3×10^{-4} (10) for Q , the forces predicted at the right and left hand are listed for the values of P , and γ .

A similar model can be constructed for the steel shot tool, which was operated without handles. Eq. (6) models the forces and moments of the observed steel shot gun.

$$\sum M_g = 0 \Rightarrow F_{Ly} * c - F_{Ry} * d = 0,$$

$$\sum F_x = 0 \Rightarrow F_{Lx} + F_{Rx} - F = 0,$$

$$\sum F_y = 0 \Rightarrow F_{Ly} + F_{Ry} - W = 0. \quad (6)$$

The variables in Eq. (6) were defined similar as in Eq. (1), except that (1) the direction of F , the drag force of steel shot mesh, was simplified as horizontally backward, and (2) the relationship among a , b , c , and d was assumed as $a = b = 0$, $c = d$.

Then, to model an operator using the tools, a hypothetical, right-handed 50th percentile US male, with a height of 1.77 m (69.7 inches) and a weight of 75.1 kg (165.6 lbs) (University of Michigan, 1999) operator was selected. Fig. 3 illustrates the two-dimensional free body diagram drawn to analyze the forces and moments at the wrists for the subject for each tool. The diagrams assume identical wrist postures of flexion, extension, and rotation, and only consider the wrist ulnar/radial deviation.

The moments at the wrists are determined by Eq. (7):

$$\sum M_L = 0 \Rightarrow M_L - W_h * m_h - F'_{Ly} * m_h = 0,$$

$$\sum F_{Lx} = 0 \Rightarrow R_{Lx} - F'_{Lx} = 0,$$

$$\sum F_{Ly} = 0 \Rightarrow R_{Ly} - F'_{Ly} - W_h = 0,$$

$$\sum M_R = 0 \Rightarrow M_R - W_h * m_h - F'_{Ry} * m_h = 0,$$

$$\sum F_{Rx} = 0 \Rightarrow R_{Rx} - F'_{Rx} = 0,$$

$$\sum F_{Ry} = 0 \Rightarrow R_{Ry} - F'_{Ry} - W_h = 0, \quad (7)$$

where W_h is the hand weight, and m_h is the moment arm of the hand at the wrist joint.

F'_{Lx} and F'_{Ly} are the forces at the left hand, while F'_{Rx} and F'_{Ry} are the forces at the right hand. According to Newton's third law, the forces at the hands equal the forces on the tools. R_{Lx} and R_{Ly} are the reaction forces at the left wrist, and R_{Rx} and R_{Ry} are the forces at the right wrist. M_L and M_R are the moment at the left and right wrists, respectively. Table 5 compares steel shot to hydroblasting with flow rates and apertures assumed to be observed typically in cleaning or surface removing operations.

References

- Buchholz, B., Paquet, V., Punnett, L., Lee, D., Moir, S., 1996. PATH: a work sampling-based approach to ergonomic job analysis for construction and other non-repetitive work. *Appl. Ergon.* 27, 177–187.
- Chaffin, D.B., Andersson, G.B.J., Martin, B.J., 1999. *Occupational Biomechanics*. 3rd ed. Wiley-Interscience, Inc., New York.
- Hudock, S., 2003. *Compendium of Ergonomic Analyses of Shipyard Work Processes and Associated Appendices: Appendix D*. US Department of Health and Human Services. Centers for Disease Control and Prevention. National Institute for Occupational Safety and Health. Cincinnati, Ohio May 2003. (<http://www.cdc.gov/niosh/ergship/>).

- Karhu, O., Hansi, P., Huorinka, I., 1977. Correcting working postures in industry; a practical method for analysis. *Appl. Ergon.* 8, 199–201.
- NIOSH, 1998. Evaluation of Substitute Materials for Silica Sand in Abrasive Blasting. Contract No. 200-95-2946 Prepared for Department of Health and Human Services, Center for Disease Control and Prevention, and National Institutes of Occupational Safety and Health Prepared by KTA-Tator, Inc. Pittsburgh, PA (http://www.cdc.gov/niosh/pdfs/ab_p2rep.pdf).
- Pan, C., Gardner, L., Landsittel, D., Hendricks, S., Chious, S., Punnet, L., 1999. Ergonomic exposure assessment: an application of the PATH systematic observation method to retail workers: postures, activities, tools and handling. *Int. J. Occ. Environ. Health* 5, 79–87.
- Paquet, V., Buchholz, B., Woskie, S., Punnett, L., 1996. Distributions of the percent of time highway construction workers spend in awkward truck postures: implication for measurement strategies and data analyses for non-repetitive work. Human Factors and Ergonomics Society-40th Annual Meeting, Philadelphia, PA.
- Paquet, V., Punnet, L., Buchholz, B., 2001. Validity of fixed-interval observations for postural assessment in construction work. *Appl. Ergon.* 32, 215–224.
- Porter, D.W., Hubbs, A.F., Robinson, V.A., Battelli, L.A., Greskevitch, M., Barger, M., Landsittel, D., Jones, W., Castranova, V., 2002. Comparative pulmonary toxicity of blasting sand and five substitute abrasive blasting agents. *J. Toxicol. Environ. Health A* 65 (16).
- Punnett, L., Paquet, V., 1996. Ergonomic exposures to carpenters and carpentry laborers in tunnel construction. In: Mital, A., et al. (Eds.), *Advances in Occupational Ergonomics and Safety I* (Proceedings of the XIth International Occupational Ergonomics and Safety Conference). IOS Press, Amsterdam.
- Rockefeller, K., 2002. Ergonomics demonstration project: skilled nursing facility. *Appl. Occup. Environ. Hyg.* 17, 470–474.
- The University of Michigan, Center for Ergonomics, 1999. Three Dimensional Strength Prediction Program, v4.2: User's Manual.
- WJTA, 1994. Recommended Practices for the Use of Manually Operated High Pressure Waterjetting Equipment. 3rd ed. WaterJet Technology Association, St. Louis, Missouri.
- <http://www.aqua-dyne.com>. AQUA-DYNE, Inc., a leading manufacturer of high pressure and ultra high pressure waterjetting systems and accessories. Information about the hydroblasting wand used in the biomechanical model was obtained.
- <http://www.marcousa.com>. Marco, Inc., a company for abrasives, blasting, and painting supplies. Information about the steel shot blasting tool was learned.

Further reading

- <http://www.sspc.org>. Steel Structures Painting Council, a non-profit professional society concerned with the use of coatings to protect industrial steel structures. Information about steel shot blasting was obtained.
- <http://www.wjta.org>. WaterJet Technology Association, provide a means of service and communication within the waterjetting industry. Information about hydroblasting was acquired.