EVALUATION OF DIFFERENT PNEUMATIC PRESSURE LEVELS AND TOOL TYPES FOR REDUCING HAND-ARM VIBRATION AND DUST EXPOSURES AT A FOUNDRY

By

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ABSTRACT

Occupational exposures to hand-arm vibration and dust have been shown to have deleterious human health effects. Exposure to vibration from pneumatic tools can result in Hand-arm Vibration Syndrome (HAVS), which is a collection of vascular, sensorineural, and musculoskeletal disorders. Exposure to dust can result in a variety of adverse respiratory symptoms. The use of a low-frequency, high-magnitude sand rammer tool during mold-making processes at a foundry could result in significant exposure to these hazards, thus it is important to mitigate the associated risks in order to ensure worker safety. The goal of this study was to evaluate whether different pneumatic pressure levels and sand rammer types have an effect on reducing hand-arm vibration and dust exposures at a foundry. Vibration and dust measurements were obtained at three different pneumatic pressure levels (90 psi, 80 psi, 70 psi) and for three different sand rammer types (LM, SM, T). The primary concern of the study was reducing hand-arm vibration exposure. Measurements were taken in compliance with ISO 5349-1 resulting in frequency-weighted, root-mean-square (rms) acceleration values (m/s^2). Significant differences in mean rms acceleration were observed across all pneumatic pressure levels and sand rammer types. At 90 psi the mean rms acceleration value was 25.53 m/s^2, decreasing to 19.58 m/s^2 at 80 psi, and further decreasing to 18.38 m/s^2 at 70 psi. The mean rms acceleration values were 19.63 m/s^2 for sand rammer LM, 21.46 m/s^2 for SM, and 19.95 m/s^2 for T. The results of this study indicate that reducing pneumatic pressure levels can reduce vibration exposure in the workplace when using low-frequency, high-magnitude tools. The results also indicate that the use of different sand rammer types produces differences in vibration exposure when tested across all pneumatic pressure levels. Dust measurements were taken concurrently with vibration measurements. The

number of dust particles was counted for each pneumatic pressure level and sand rammer type. Overall, the mean particle count for the dust measurements was the highest at 90 psi (41,681) followed by 70 psi (33,514), and 80 psi (26,047). Sand rammer SM had the highest mean dust particle count at 35,732, followed by T at 34,460, and LM at 31, 382. The results indicate that lowering pneumatic pressure levels could potentially reduce dust exposure in the workplace when using a percussive tool such as a sand rammer. However, variability in the sampling conditions related to dust measurements weaken the association.

INTRODUCTION AND BACKGROUND

Foundries employ nearly 130,000 people in the United States across a variety of operations (BLS, 2016). Processes at a foundry include furnace preparation, melting and pouring metal, sand preparation and handling, making and preparing patterns, grinding, core-making, and mold-making. The most common method for making molds at a foundry is the use of green sand which is compacted around a specific pattern (EPA, 1981). This method is referred to as "sand-casting." These foundry processes can result in numerous health hazards from chemical, physical, and ergonomic exposures (Koskela, Hernberg, Kärävä, Järvinen, & Nurminen, 1976).

Exposures related to vibration and dust from the use of a sand rammer are of particular concern for mold-makers. A sand rammer is a pneumatic, hand-held, high-impact tool which uses a piston-controlled rod and butt to deliver rapid compacting movements in order to create a mold. Figure 1 shows an example of a sand rammer used at a foundry.

Figure 1: A sand rammer used to compact sand around a pattern at a foundry

Repeated exposure to hand-transmitted vibration from powered tools can result in musculoskeletal, sensorineural, and vascular disorders which are generally referred to as hand-arm vibration syndrome (HAVS) (Heaver, Goonetilleke, & Shiralkar, 2011). One of the vascular manifestations of HAVS is a condition known as secondary Reynaud's Phenomenon, also referred to as vibration-induced white finger (VWF). Symptoms of VWF include tingling, numbness, loss of feeling in the fingers and toes, whitening and blanching of fingers, and blue skin. Exposure to cold temperatures and stress are known to exacerbate the condition. Epidemiological evidence associates the professional use of vibratory tools to the prevalence of VWF in the workplace based on the duration, magnitude, and frequency of exposure (Griffin, 1990; Bovenzi, 1998; Bovenzi 2010).

The National Institute for Occupational Safety and Health (NIOSH) conducted an epidemiological study to determine the incidence and latency period for VWF in foundry and shipyard workers exposed to vibration from using pneumatic chipping and grinding tools. The cohort of 235 workers had no confounding histories of exposure, and the control group had never before used a hand-held vibrating tool. VWF was found in nearly half of the exposure group for foundry workers and 19 percent of the exposure group for shipyard workers, while none of the control group had VWF. The foundry workers experienced a median latency period of 1.4 years for the blanching of fingers in foundry workers, and 16.5 years for the shipyard workers. The researchers concluded that prolonged use of pneumatic tools presents a significant risk for VWF in certain occupational settings (Wasserman, 1982).

The low-frequency, high magnitude movement of sand rammers has been known to be a contributor to hand-arm vibration exposure in the workplace (Tominaga, 2005;

Bovenzi, 2012). Evidence suggests that low-frequency tools, such as sand rammers, are more closely associated with musculoskeletal disorders of the wrist, elbow, and shoulder, while high frequency tools are more closely associated with disorders of the hand and VWF. Dong et al. (2008) conducted a study in which a model was used to analyze the absorbed power distribution for parts of the body exposed to hand-arm vibration. The study found that the power absorption distribution from vibration exposure to low-frequency tools was mostly through the arm and shoulder. For high-frequency tools such as grinders, the power absorption was mostly distributed through the fingers and hand. This is consistent with previous measurements of transmissibility which indicate that transmission of vibration along the joints and bones are related to low-frequency, whereas the hand has marked attenuation at high-frequency (Suggs, 1974). Another study was conducted to determine if the use of impact tools is associated with more symptoms of exposure than non-impact tools in a population of 312 workers. The researchers also looked at whether the use of low-frequency impact tools is more associated with proximal symptoms of exposure than high-frequency tools. The researchers concluded that elbow and shoulder symptoms were most closely associated with low-frequency tools, while hand and wrist symptoms were related to high-frequency tools (Kihlberg & Hagberg, 1997). Other studies provide evidence showing low-frequency tools are more related to vibration-induced symptoms of the wrist, elbows, and shoulders, as opposed to fingers and hands (Tominaga 1993; Gemne, Saraste, Christ, & Dupuis, 1987).

It is believed that prolonged work with low-frequency, percussive tools can lead to osteoarthrosis of the joints in the upper-extremities. Studies utilizing radiological evidence have shown a significant increase in the frequency of osteoarthrosis in the vibration exposed groups compared to the controls (Lawrence, 1955; Lie, 1980). Bovenzi, Fiorito, and Volpe (1987) conducted a study to determine joint and bone damage in vibration-exposed foundry workers using radiological signs to determine musculoskeletal symptoms. The control group was comparable referents who performed manual labor but were not vibration-exposed. There was a significantly higher prevalence of osteoarthritis in the exposed group compared to the control group. Also, olecranon spurs were shown to be highly prevalent in the exposed subjects; the researchers noted this was common among workers using percussive tools. The authors found no relation between VWF and radiological changes in the upper extremities among the workers exposed to vibration.

Gemne et al. (1987) conducted a comprehensive review on vibration-induced bone and joint disorders. The study determined there was an excess risk for osteoarthrosis of the wrist and elbow in workers exposed to low-frequency, high-magnitude tools. There was no association between excess joint and bone damage and the use of high-frequency tools. Researchers believe the etiology of the wrist and elbow abnormalities is not only specific to vibration exposure, but is also specific to the physical nature of controlling a low-frequency, percussive tool. Static and dynamic loading in awkward postures, joint positioning and stabilization, gripping and pressing forces, and other biomechanical factors are believed to play a role in bone and joint damage related to low-frequency, high magnitude tools (Bovenzi, 1990; Gemne et al., 1987).

The formation of vacuoles, bone cysts and pseudoarthrosis from vibration exposure to percussive tools has been documented. However, contradictory results and the lack of prospective studies weaken the validity of the association (Gemne et al., 1987). There has been substantial research related to the vascular and neurological components of HAVS, however the musculoskeletal component is greatly under-represented in research. Vibration exposure is evaluated based on recommendations, guidelines, and methods outlined in international standard ISO 5349-1 (2001). Evaluation is based on a dose-response relationship for determining the onset of vibration-induced white finger over an eight-hour equivalent exposure A(8). The American Conference of Governmental Industrial Hygienists (ACGIH) also establishes its threshold limit values (TLVs) for hand-arm vibration based on the presence of VWF (ACGIH, 2016). However, these standards and guidelines fail to take into account the onset of musculoskeletal disorders.

Dust exposure presents a significant health concern for workers at a foundry. Dust exposure can lead to lung irritation and inflammation, allergic responses such as asthma, skin effects, infection, systemic poisoning, pneumoconiosis, and cancer. Exposure is generally dependent on the aerodynamic particle diameter, exposure duration, and air (mass) concentration (WHO, 1999).

The adverse health effects from dust exposure in foundries has been well documented. A cross-sectional study was conducted to determine the prevalence of occupational asthma and other respiratory symptoms at a foundry. The manifestation of respiratory symptoms was found to be significantly higher in the exposed group than the control group (Kayhan, Tutar, Cinarka, Gumus, & Koksal, 2013). Another study at a foundry showed a decrease in lung function as exposure increased based on spirometry measurements. The specific job performed, as well as exposure to high concentrations of respirable dust were significant predictors for a reduction in lung function (Gomes, Lloyd, Norman, & Pahwa, 2001). The prevalence of pneumoconiosis and silicosis has also been shown to be a primary health concern for foundry workers (Mclaughlin, 1957; Rosenman et al., 1996; Zhang et al., 2010).

Vibration exposure originating from prolonged use of a sand rammer to compact molds at a foundry has the potential to produce serious adverse health effects. Previous research has shown that exposure to low-frequency, high magnitude pneumatic tools can lead to musculoskeletal disorders which include joint and bone damage to the wrist, elbow, and shoulder. Dust exposure is also a concern for mold-makers due to the impact of the sand rammer on the olivine sand. Dust exposure has been shown to cause numerous respiratory illnesses including pneumoconiosis and silica. The risk of vibration and dust exposures is high at a foundry; controls should be implemented to ensure worker health and safety.

SPECIFIC AIMS AND HYPOTHESIS

The first aim of this study was to determine if human hand-arm vibration exposure to a sand rammer during sand-casting operations at a foundry will change if pneumatic pressure is reduced. To the best of our knowledge, there are no studies that evaluate whether hand-arm vibration exposure changes based on different pneumatic pressure levels. It is hypothesized that there will be no differences in vibration exposure from the reduction of pneumatic pressure. The second aim of this study was to determine if human hand-arm vibration exposure changes as a function of tool design and condition. It is hypothesized that there will be no differences in vibration exposure as a function of tool design and condition. The third aim of this study was to determine if dust exposure during sand-casting operations at a foundry changes as pneumatic pressure is reduced. It is hypothesized that there will be no differences in dust exposure as pneumatic pressure is reduced. The fourth aim of this study is to determine if dust exposure changes as a function of tool design and condition. It is hypothesized that there will be no differences in dust exposure as a function of tool design and condition.

METHODS

Sand Casting Process

The sampling site was a foundry located in Arizona specializing in brass, bronze, and aluminum castings. The focus of this study was on the single-man operated aluminum line where the sand-casting process occurred. Olivine sand was poured from the hopper, a pneumatic and counter-weight operated chute which distributes the sand, into a casting flask. The casting flask was a divided frame which consisted of the cope (top half) and the drag (bottom half), with the pattern for the mold connected between them. Initially, a small amount of sand was poured into the drag and sifted before making contact with the pattern in order to preserve detail. A larger amount of sand was added to the flask, and the sand rammer was used to compact the sand around the pattern. A second amount of sand was added to the flask, and the sand rammer was again used to compact the sand. The casting flask was turned over, and the cope was filled with sand and compacted with the sand rammer. A pneumatic vibrator was used to separate the cope from the drag, and the pattern was removed. After inspecting the mold for flaws, it was transferred to the pouring line. The flask was removed, and the mold was then fastened together in preparation for the metal pouring process. The cope, drag, and pattern were reconnected and placed under the hopper in preparation for the next mold.

Data Collection (Vibration)

Three different types of sand rammers (LM, SM, T) were measured at three different pneumatic air pressure settings (70 psi, 80 psi, 90 psi), equating to nine sampling conditions. The same worker and sand casting station were sampled all three days. The air pressure was adjusted through a pressure regulator connected to the air-line as it entered the work station. The LM and SM sand rammers were refurbished tools on temporary loan through Michigan Pneumatic Tool Inc., while the T sand rammer belonged to the foundry and had been extensively used. LM and T were "0" sized sand rammers, and were larger than the "00" sized SM sand rammer. A Piezotronics HVM100 (Larson Davis, Depew, NY) was used to measure the worker's vibration exposure to the sand rammers. The instrument evaluates vibration exposure in compliance with ISO 5349-1, measuring three orthogonal directions simultaneously (x, y, z axes), resulting in the vector sum of the three axes. The vector sum is a frequency-weighted, root-mean squared (rms) average acceleration. The rms average of the vibration was indicated by the acceleration of the tool relative to where it contacted the hand, and was reported by the HVM100 in meters per second squared (m/s^2). The averaging time for the measurements was every one second. The instrument performed 6,000 measurements within each second, taking the average of these measurements to calculate the rms acceleration. The HVM100 handle adapter was placed on the sand rammer between the tool and the worker's hand. The triaxial accelerometer was attached to the handle adapter and connected to the HVM100 via cable. Sampling for each of the nine conditions was continuous through the duration of time it took the worker to complete four molds. The vibration measurement data was stored and analyzed through BLAZE software (Larson Davis, version 6.2.1, 2014).

Data Collection (Dust)

A KANOMAX Model 3887 Handheld Laser Particle Counter (KANOMAX, Andover, NJ) was used to measure airborne dust during sand casting operations. The instrument counted the number of dust particles passing over a sensor in a specified period of time. The instrument measured three particle sizes (0.3 µm and larger, 0.5 µm and larger, 5.0µm and larger) simultaneously via an internal laser diode, and sampled at a flow rate of 2.83 L/min. The same worker and sand casting station were sampled all three days, and dust samples were taken concurrently with vibration samples. The instrument was placed on a stand in close proximity to the worker at chest height, and remained in that position for all three days of sampling. The instrument was set for a single measurement that automatically stopped after a ten second sampling time had elapsed. The ten second sampling interval was started once the sand rammer was in use compacting the sand. An automated ten second run time with a filter tube over the inlet was used to clean the instrument between samples. Sampling for each of the nine conditions lasted the time it took the worker to complete four molds. The sampling data was stored on the instrument and exported for analysis.

Data Analysis

Statistical analysis of the vibration and dust samples was performed using STATA (12.0, 2011). Analysis of variance (ANOVA) was used to determine significant differences in vibration measurements. ANOVA was used because the study had two categorical independent variables (psi, sand rammer type) with three groups each, and one continuous dependent variable (rms acceleration). Multiple one-way ANOVAs were conducted in order to determine if there were any significant differences in vibration measurements at specific pneumatic air pressure levels across different sand rammer types, and for specific sand rammer types across different air-pressure levels. A two-way ANOVA was used determine if there were significant differences in vibration measurements at different pneumatic air pressure levels regardless of sand rammer types, as well as significant differences for different sand rammers regardless of air-pressure levels. It was also conducted to determine if there was an interaction between sand rammer types and pneumatic pressure levels on vibration exposure. Lastly, descriptive statistics were used to determine relevant patterns in the dust data concerning whether the different sampling conditions would change a worker's dust exposure when using a sand rammer.

RESULTS

Results for vibration measurements (m/s^2) showing the mean, standard deviation, and sample size at different pneumatic pressure levels and for different sand rammer types are found in Table 1. The sample size (n) refers to the number of seconds the sand rammer was used over the course of making four molds. The greatest duration occurred at 70 psi (n=749), followed by 80 psi (n=573), and 90 psi (n=392). The greatest duration occurred when using the SM sand rammer (n=654), followed by LM (n=588), and T (n=472). The means of the rms acceleration measurements decreased as the pneumatic pressure level was reduced, with the exception of sand rammer T from 80 psi to 70 psi.

Table 1: Stratified table showing vibration measurements (m/s^2) for different pneumatic pressure levels (70, 80, 90 psi) and sand rammer types (LM, SM, T).

	Sand Rammer Type			
	LM	**SM**	**T**	**Total Rammer***
PSI 70				
n	281	259	209	749
Mean RMS Acceleration (m/s^2)	17.27	19.35	18.68	18.38
std dev	5.13	4.33	2.90	4.41
PSI 80				
n	197	224	152	573
Mean RMS Acceleration (m/s^2)	20.49	19.63	18.35	19.58
std dev	4.51	4.70	2.95	4.31
PSI 90				
n	110	171	111	392
Mean RMS Acceleration (m/s^2)	24.13	27.07	24.53	25.53
std dev	6.55	6.48	5.92	6.48
Total PSI **				
n	588	654	472	1714
Mean RMS Acceleration (m/s^2)	19.63	21.46	19.95	20.42
std dev	5.83	6.09	4.60	5.68

*Total Rammer: acceleration measurements ranging across all sand rammer types.
**Total PSI: acceleration measurements ranging across all psi levels

The distribution of the rms acceleration measurements was evaluated across pneumatic pressure levels and sand rammer types to determine if the data was approximately normal. Figure 2A illustrates the distribution across pneumatic pressure levels. 70 psi and 80 psi were approximately normally distributed, while 90 psi is slightly negatively-skewed. Figure 2B illustrates the distribution across sand rammer types. LM and SM were approximately normally distributed, while T was slightly positively-skewed. The differences in the means of the vibration measurements are more apparent for the pneumatic pressure levels than the sand rammer types.

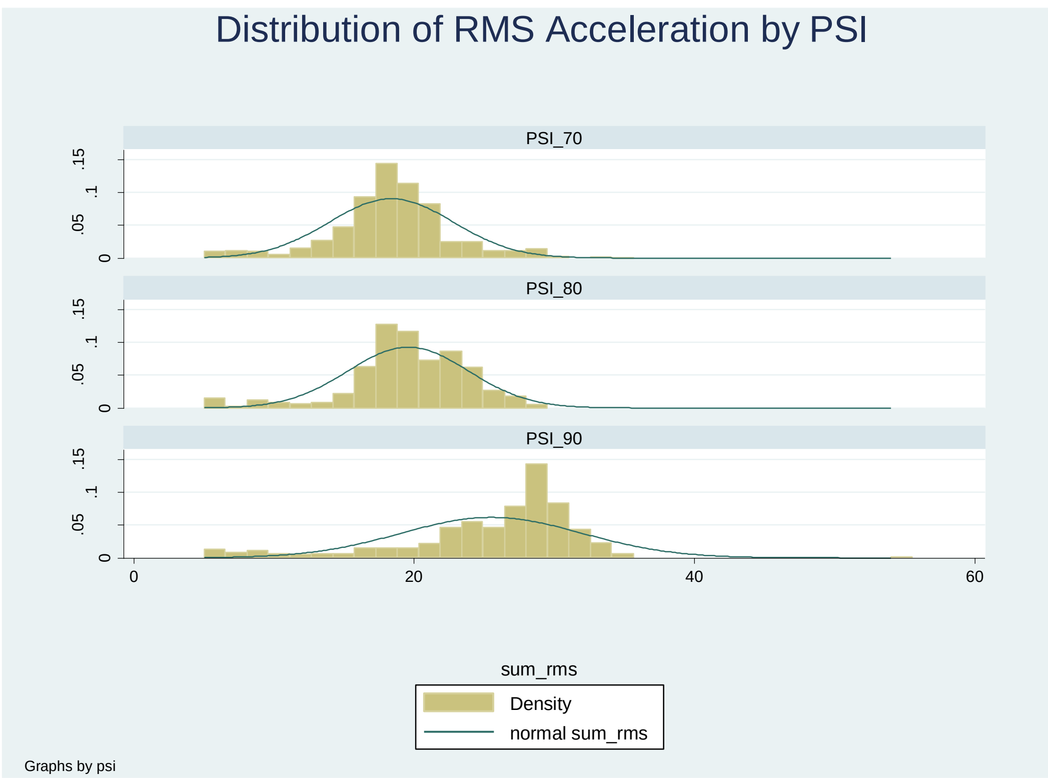

Figure 2A: Distribution of rms acceleration values across all pneumatic pressure levels

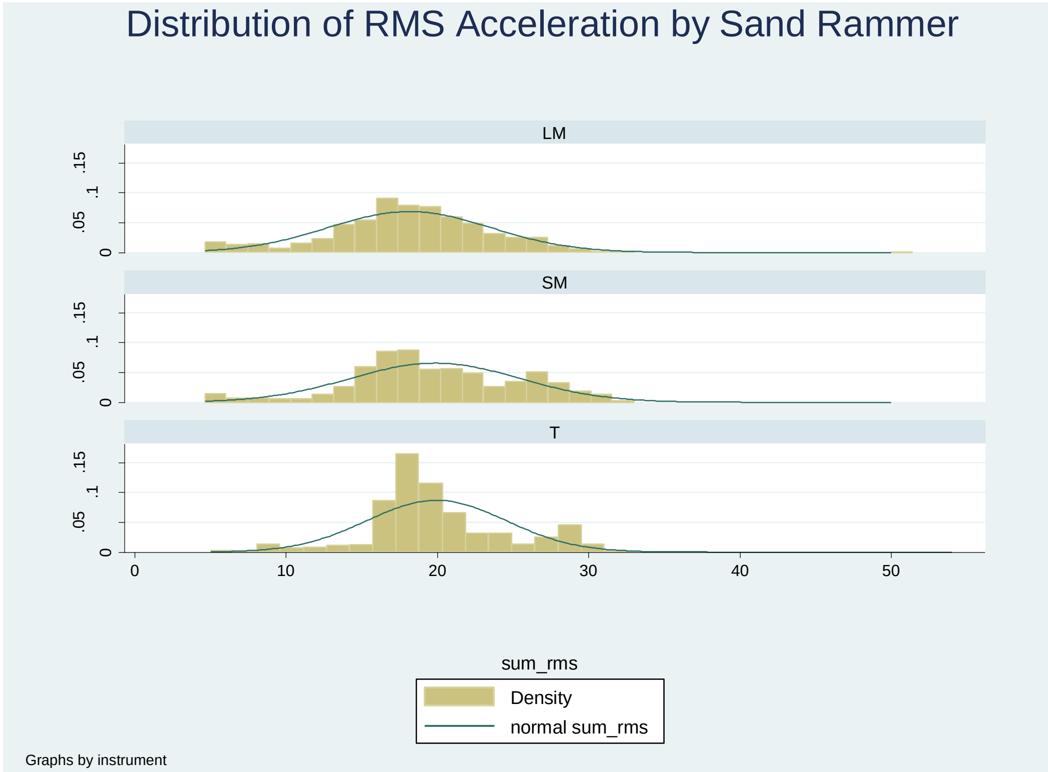

Figure 2B: Distribution of rms acceleration values across all sand rammer types

Multiple one-way ANOVAs were conducted in order to determine if there was a significant difference in the vibration exposure (m/s^2) for each sand rammer type (LM, SM, T) at three different pneumatic pressure levels (70 psi, 80 psi, 90 psi). Since $p<0.05$ ($p=0.000$), we reject the null hypothesis and conclude there is a statistically significant difference in vibration exposure at three different pneumatic pressure levels for each of the sand rammer types. These results are shown in Table 2.

Table 2: Results of one-way ANOVAs for vibration measurements (m/s^2) at three different pneumatic pressure levels for sand rammer types LM, SM, and T

Sand Rammer: LM				
PSI	**Mean RMS Acceleration (m/s^2)**	**std dev**	**F-Statistic**	**P-value**
70	17.27	5.13	71.81	<0.0001
80	20.49	4.51		
90	24.13	6.55		
Sand Rammer: SM				
PSI	**Mean RMS Acceleration (m/s^2)**	**std dev**	**F-Statistic**	**P-value**
70	19.35	4.33	140.33	<0.0001
80	19.63	4.70		
90	27.07	6.48		
Sand Rammer: T				
PSI	**Mean RMS Acceleration (m/s^2)**	**std dev**	**F-Statistic**	**P-value**
70	18.68	2.90	103.47	<0.0001
80	18.35	2.95		
90	24.53	5.92		

Multiple one-way ANOVAs were conducted in order to determine if there was a significant difference in the vibration exposure (m/s^2) at each pneumatic pressure level (70, 80, 90 psi) for three different types of sand rammers (LM, SM, T). Since $p<0.05$ ($p=0.001$), we reject the null hypothesis and conclude there is a statistically significant difference in vibration exposure for three different sand rammers at each pneumatic pressure level. These results are shown in Table 3.

Table 3: Results of one way ANOVAs for vibration measurements (m/s^2) for three different sand rammer types at each pneumatic pressure level (70 psi , 80 psi, 90 psi)

Sand Rammer	**Mean RMS Acceleration (m/s^2)**	**std dev**	**F-Statistic**	**P-value**
PSI 70				
LM	17.30	5.13	16.30	<0.0001
SM	19.35	4.33		
T	18.68	2.90		
PSI 80				
Sand Rammer	**Mean RMS Acceleration (m/s^2)**	**std dev**	**F-Statistic**	**P-value**
LM	20.49	4.51	10.9	<0.0001
SM	19.63	4.70		
T	18.35	2.95		
PSI 90				
Sand Rammer	**Mean RMS Acceleration (m/s^2)**	**std dev**	**F-Statistic**	**P-value**
LM	24.13	6.55	9.08	<0.0001
SM	27.07	6.48		
T	24.53	5.92		

A two-way ANOVA was conducted to determine if there was any significant differences in vibration exposure (m/s^2) based on different pneumatic pressure levels (70 psi, 80 psi, 90 psi) regardless of sand rammer type. Since $p<0.05$ ($p=0.0000$) we reject the null hypothesis and conclude there is a significant statistical difference in vibration exposure at different pneumatic pressure levels. It was also used to determine if there was any significant difference in vibration exposure (m/s^2) based on different sand rammer types (LM, SM, T), regardless of pneumatic pressure levels. Since $p<0.05$ ($p=0.0000$), we reject the null hypothesis and conclude there is a significant statistical difference in vibration exposure (m/s^2) when using different sand rammer types. Finally, it was conducted to determine if there was any significant interaction between the pneumatic pressure levels and sand rammer types on vibration exposure (m/s^2). Since $p<0.05$ ($p=0.0000$), we reject the null hypothesis and conclude there is a statistically significant interaction between different pneumatic air pressure levels and sand rammer types on vibration exposure. These results are shown in Table 4.

Table 4: Results of two-way ANOVA for determining statistical significance of pneumatic pressure levels, sand rammer types, and the interaction between them

	F-statistic	**P-value**
Sand Rammer (LM,SM,T)	16.85	<0.0001
PSI (70,80,90)	259.17	<0.0001
Sand Rammer*PSI**	11.24	<0.0001

**Sand Rammer*PSI: The interaction between psi levels and sand rammer types on the RMS acceleration measurements

Results for dust particle counts showing the mean, standard deviation, and sample size at different pneumatic pressures and for different sand rammer types are found in Table 5. The mean particle count was highest at 90 psi (41,681), followed by 70 psi (33,514), and 80 psi (26,047). Standard deviation values were high for pneumatic pressure measurements when tested regardless of the specific sand rammer type. The mean particle count was highest for sand rammer SM (35,732), followed by T (34,460), and LM (31, 382). Standard deviation values were also high for sand rammer types when tested regardless of the specific pneumatic pressure level.

Table 5: Stratified table showing summary statistics of dust particle counts for different pneumatic pressure levels and sand rammer types

		Sand Rammer			
		LM	**SM**	**T**	**Total****
PSI 70	**n**	11	12	9	32
	Mean Particle Count*	40460	37302	19972	33514
	std dev	24717	22189	4960	21308
PSI 80	**n**	11	12	12	35
	Mean Particle Count*	20036	18814	38790	26047
	std dev	3841	4440	12153	12082
PSI 90	**n**	12	13	12	37
	Mean Particle Count*	33462	49899	40997	41681
	std dev	11257	27835	11922	19684
Total*+	**n**	34	37	33	104
	Mean Particle Count*	31382	35732	34460	33906
	Std Dev	17430	24155	13707	19053

*Mean Particle Count: the sum of the three particle sizes (0.3µm, 0.5µm, 5.0µm) for each measurement, averaged across each sampling condition

**Total: dust measurements ranging across all sand rammer types

*+Total: dust measurements ranging across all psi levels

DISCUSSION

Vibration exposure has been shown to have deleterious health effects in an occupational setting. Exposure to vibration has been associated with vascular, neurological, and musculoskeletal disorders, as well as carpal-tunnel syndrome. Based on these health effects it is important to minimize vibration exposures in the workplace. There are currently no standards related to vibration exposure in the US. The ACGIH TLV which should not be exceeded for less than one hour of daily hand-arm vibration exposure is 12 m/s^2. The European Union (EU) Vibration Directive 2002/44/EC (2002) establishes a daily exposure action value of 2.5 m/s^2, and a daily exposure limit of 5 m/s^2. All rms acceleration mean values across the different sampling conditions exceeded these exposure limits, indicating that the foundry workers are significantly overexposed to hand-arm vibration.

There were significant differences in the means of the vibration measurements at specific pneumatic air pressure levels across each sand rammer type, and for specific sand rammer type across each pneumatic pressure level (Tables 2, 3). There were also significant differences at different pneumatic pressure levels regardless of sand rammer type, as well as significant differences for different sand rammers regardless of pneumatic pressure level. The interaction between pneumatic pressure level and sand rammer type on the rms acceleration measurements was also shown to be significant (Table 4). Figure 2A shows the distribution of the rms acceleration measurements was approximately normal across the three sand rammer types (LM, SM, T). Figure 2B shows the distribution of the rms acceleration measurements was approximately normal at 80 psi and 70 psi, while 90 psi was slightly negatively skewed. ANOVA is robust against non-normality (Schmider, Ziegler, Danay, Beyer, & Buhner, 2010), so the distribution at 90 psi would have little effect on the outcome. Equal variance was assumed for each test because a continuous dependent variable was analyzed against two categorical independent variables, the measurements were obtained under the same conditions, and no significant differences were hypothesized.

Overall there was a decrease in the means of the vibration measurements as the pneumatic pressure levels were lowered. At 90 psi the mean rms acceleration value was 25.53 m/s^2, decreasing to 19.58 m/s^2 at 80 psi, and further decreasing to 18.38 m/s^2 at 70 psi regardless of specific sand rammer types (Table 1). These results show that the greatest decrease in mean rms acceleration values occurred from 90 psi to 80 psi. Table 2 shows that for each pneumatic pressure level tested, there was a decrease in mean rms acceleration values when tested across each sand rammer type, with the exception of sand rammer T which showed an increase from 80 psi (18.35 m/s^2) to 70 psi (18.68 m/s^2). This could be due to the problem that arose from using the in-line pressure regulator. The pressure regulator was initially placed between the sand rammer and the air hose. However, the impact from the sand rammer caused the pressure to decrease from where it was initially set. This occurred while testing at 80 psi. The problem was resolved by moving the in-line pressure regulator to the point where the air-line entered the work-station, thus avoiding the impact from the tool. Retesting at 80 psi occurred the following day, however the T sand rammer broke and could no longer be used. Thus, retesting never occurred for the T sand rammer at 80 psi.

The mean rms acceleration values were 19.63 m/s^2 for sand rammer LM, 21.46 m/s^2 for SM, and 19.95 m/s^2 for T. These values were obtained regardless of specific pneumatic pressure levels. Notably, sand rammer LM had the lowest value at 19.63 m/s^2 (Table 1). No clear pattern showing a consistent change in vibration exposure emerged when testing each sand rammer type across each pneumatic pressure level. Sand rammer LM had the lowest mean rms acceleration values relative to the other sand rammers at 70 psi (17.30 m/s^2), the highest value at 80 psi (20.49 m/s^2), and the lowest again at 90 psi (24.13 m/s^2). Sand rammer SM had the highest mean rms acceleration values relative to the other sand rammers at 70 psi (19.35 m/s^2), and 90 psi (24.13 m/s^2). This inconsistency could indicate that sand rammers varying in size and condition may operate differently at different pneumatic pressure levels. This could potentially impact the level of exposure to a worker, and should be investigated further.

Table 1 shows the sample size (n) for each of the sampling conditions. The sample size is defined as the number of seconds the sand rammer was used for the duration of time it took the worker to complete four molds. The HVM100 records and stores the rms acceleration measurements every one second, thus the sample size represents the number of seconds the sand rammer was in use. Table 1 shows the sand rammers were in use the most at 70 psi (n=749), followed by 80 psi (n=573), and 90 psi (n=392). These results were obtained regardless of the specific type of sand rammer being used. Also, for each of the sand rammers tested, there was an increase in the duration of ramming as the pneumatic pressure levels were reduced. Overall, sand rammer SM had the largest sample size (n=654), followed by LM (n=588), and T (n=472). These values were obtained regardless of pneumatic pressure levels.

The results of this study indicate that reducing pneumatic pressure levels can reduce vibration exposure in the workplace when using low-frequency, high-magnitude tools. This is indicated by the decreasing mean values for the vibration measurements as the pneumatic pressure level is reduced (Table 1), as well as the statistical significance of the means (Table 2). The greatest reduction in vibration exposure occurred when pressure levels were reduced from 90 psi (25.53 m/s^2) to 80 psi (19.58 m/s^2). This was also true when tested across each specific sand rammer. There was only a small decrease in vibration exposure from 80 psi (19.58 m/s^2) to 70 psi (18.38 m/s^2). 70 psi was also associated with the greatest amount of time spent using the sand rammer to compact the molds (n=749), which suggests that 80 psi is the best option for reducing vibration exposure relating to the different pneumatic pressure levels tested. The foundry uses 90 psi as its standard pneumatic pressure level which is consistent across industrial settings. Reducing the pressure from 90 psi to 80 psi has the potential to significantly reduce vibration exposure in the workplace.

Table 1 also indicates that the use of different sand rammer types produces differences in vibration exposure when tested across all pneumatic pressure levels, however the differences in the mean values were small (19.63 m/s^2, 21.46 m/s^2, 19.95 m/s^2). The differences in vibration exposures were also small for the three sand rammers when tested at each specific pneumatic pressure level (Table 3). The large sample size likely contributed to the differences being significant (n=1714). Based on the evidence in Table 1, it is unclear which of the sand rammers tested is more closely linked to an increase or reduction in vibration exposure. This could suggest that sand rammers generally produce similar vibration exposure levels regardless of the model, condition, or difference in pneumatic pressure levels.

One of the aims of this study was to determine if different pneumatic pressure levels resulted in changes in vibration exposure. The results of this study have determined that vibration exposure can be reduced as pneumatic pressure is lowered. However, reducing pneumatic pressure levels may indirectly increase vibration exposure by increasing the duration a worker has to use the sand rammer in order to complete a mold. The greatest time spent using a sand rammer over the course of compacting four molds was at 70 psi (n=749). The least amount of time was at 90 psi (n=392). This could be due to the worker's familiarity with compacting molds at 90 psi, which is the pneumatic pressure level used at the foundry. The lack of familiarity at 80 psi or 70 psi may have affected the worker's confidence in producing a quality mold. This idea could be supported by the results showing the foundry's sand rammer (T), in which the worker used every day, was associated with the least amount of time spent compacting molds (n=472) relative to the other sand rammers tested. The worker was very familiar with using sand rammer T, but had never before used the other two sand rammers (LM, SM). However, it is possible that sand rammers generally may not be as efficient at compacting molds as pneumatic pressure is lowered, which could potentially lead to a longer duration of vibration exposure over the course of a workday. Exposure is a function of magnitude and time. With a high-impact tool like a sand rammer, the magnitude is likely the most important factor for reducing vibration exposure.

Overall, the mean particle count for the dust measurements was the highest at 90 psi (41,681) followed by 70 psi (33,514), and 80 psi (26,047). The greatest reduction in dust particle counts occurred when the pneumatic pressure was lowered from 90 psi to 80 psi. Sand rammer SM had the highest mean dust particle count at 35,732, followed by T at 34,460, and LM at 31, 382. There were no consistent patterns in the means of the dust particle counts when a specific pneumatic pressure level was tested for each sand rammer type. Conversely, when each of the sand rammers was tested at a specific pneumatic pressure level there were no consistent patterns. Standard deviations were generally high showing great variability in dust particle counts across psi levels and sand rammer types

The results from analyzing the dust measurements indicate that lowering pneumatic pressure levels could potentially reduce dust exposure in the workplace when using a percussive tool such as a sand rammer. This is indicated by the sizeable decrease in mean particle counts when the pneumatic pressure is lowered below 90 psi. The mean dust particle count was the lowest at 80 psi (26,047). This was also the pressure level recommended to reduce vibration exposure based on the vibration measurements and sample size. 80 psi could be the optimal pneumatic pressure level for reducing both vibration and dust exposure during sand casting operations at a foundry. For specific sand rammer types, T was the only rammer that had a decrease in dust particles as the pneumatic pressure was lowered across each psi level. The other sand rammers showed inconsistent patterns when tested for specific sand rammer types and at specific pneumatic pressure levels. The inconsistent patterns, as well as the large standard deviation values could be indicative of the variability in environmental conditions at the foundry.

A limitation of this study was the small sample size related to the dust measurements in each sampling condition. An example of this is found in Table 5 corresponding to sand rammer T at 70 psi (n=9). Another limitation was the variability in environmental conditions at the foundry, particularly as it relates to the dust measurements. The foundry had multiple large doors which are either opened or partially opened at any point during the workday. Changes in wind velocity and/or direction could have had an impact on the dust readings. The worker also had a fan blowing on him due to the intense heat within the foundry. Though the particle counter was situated out of the fan's path, the fan may have affected the movement of the dust as it became airborne from the casting flask, potentially impacting dust measurements. The no-bake sand casting area was thirty feet away from the aluminum line being sampled, and was located directly in front of a large open door. Dust from the no-bake line, as well as wind from the open door could have also potentially affected the dust particle readings. The large variability in the dust readings may be indicative of this.

Reducing pneumatic pressure levels should be considered an option for limiting vibration exposure when using percussive tools in the workplace. However, it is important to determine if lowering pneumatic pressure levels increases vibration exposure by increasing the amount of time needed to compact a mold. It is unclear if the time increase is a product of the worker's familiarity with a specific tool at a specific pneumatic pressure level, or if lowering the pneumatic pressure levels leads to less efficacy when compacting a mold. A quality control study should be conducted at the foundry to determine if lowering the pneumatic pressure level below 90 psi will result in the production of a lower quality mold. Future research should also be conducted to determine if the magnitude of hand-arm vibration exposure has more of an impact than the duration of exposure on the health outcome of the worker.

ISO-5349-1, as well as the ACGIH TLV for hand-arm vibration exposure are based on the onset of VWF. Research has shown that the use of low-frequency, high-magnitude pneumatic tools are associated with the development of musculoskeletal disorders, and have little association with the onset of VWF. The standards, guidelines, and methods related to hand-arm vibration exposure fail to take into account the onset of musculoskeletal disorders. This suggests that a new hand-arm vibration exposure standard should be proposed which accounts for adverse health outcomes other than just VWF. Future research should look at the difference in health outcomes between high and low-frequency tools. This study will be provided to the foundry and Michigan Pneumatic Inc. in order to contribute information for reducing vibration exposure in the workplace.

In conclusion, lowering pneumatic pressure levels was shown to reduce vibration exposure by reducing the rms acceleration (m/s^2) values. Lowering the pneumatic pressure from 90 psi to 80 psi resulted in a large reduction in vibration exposure, with a small decrease occurring from 80 psi to 70 psi. Significant differences in vibration exposure were observed across all pneumatic pressure levels and sand rammer types. Overall, the three sand rammers tested had similar levels of vibration exposure, though the differences were significant. Dust exposure was reduced when the pneumatic pressure levels were lowered, with the greatest reduction occurring from 90 psi to 80 psi. Currently, there are no standards in the US related to vibration exposure. The ACGIH TLV which should not be exceeded for less than one hour of daily vibration exposure is 12 (m/s^2). All of the mean acceleration values associated with the use of a sand rammer in this study were well over the TLV. This indicates that the foundry workers are exposed to vibration at levels which could cause deleterious health effects. Due to the lack of vibration exposure standards in the US, it is the responsibility of industry to ensure the safety of their workers.

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