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Variability in hand-arm vibration during grinding operations

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Background; Measurements of exposure to vibrations from hand-held tools are often conducted on a single occasion. However, repeated measurements may be crucial for estimating the actual dose with good precision. In addition, knowledge of determinants of exposure could be used to improve working conditions. The aim of this study was to assess hand-arm vibration (HAV) exposure during different grinding operations, in order to obtain estimates of the variance components and to evaluate the effect of work postures.
Methods; Ten experienced operators used two compressed air driven angle-grinders of the same make in a simulated work task at a workplace. One part of the study consisted of using a grinder whilst assuming two different working postures: at a standard work bench (low) and on a wall with arms elevated and the work area adjusted to each operator's height (high). The workers repeated the task three times. In another part of the study, investigating the wheel wear, for each grinder the operators used two new grinding wheels and with each wheel the operator performed two consecutive one-minute grinding tasks. Both grinding tasks were conducted on weld puddles of mild steel on a piece of mild steel. Measurements were taken according to ISO-standard 5349 [the equivalent hand-arm-weighted acceleration (m/s^2) averaged over 1 min]. Mixed and random effects models were used to investigate the influence of the fixed variables and to estimate variance components.
Results; The equivalent hand-arm-weighted acceleration assessed when the task was performed on the bench and at the wall was 3.2 m/s^2 and 3.3 m/s^2, respectively. In the mixed effects model, work posture was not a significant variable. The variables 'operator' and 'grinder' together explained only 12% of the exposure variability and 'grinding wheel' explained 47%; the residual variability of 41% remained unexplained. When the effect of grinding wheel wear was investigated in the random effects model, 37% of the variability was associated with the wheel while minimal variability was associated with the operator or the grinder and 37% was unexplained. The interaction effect of grinder and operator explained 18% of the variability. In the wheel wear test, the equivalent hand-arm-weighted accelerations for grinder 1 during the first and second grinding minutes were 3.4 and 2.9 m/s^2, and for grinder 2 they were 3.1 and 2.9 m/s^2. For grinder 1, the equivalent hand-arm-weighted acceleration during the first grinding minute was significantly higher ($p=0.04$) than during the second minute.
Conclusions; Work posture during grinding operations does not appear to affect the level of hand-arm vibration. Grinding wheels explained much of the variability in this study, but almost 40% of the variance remained unexplained. The considerable variability in the equivalent hand-arm-weighted acceleration has an impact on the risk assessment at both the group and individual level.

Keywords; work posture, hand-held tools, determinants of exposure, exposure variability, hand-arm vibration, grinders

Introduction

In most EU countries, risk assessment for hand-arm vibration (HAV) is based on the International Standard ISO 5349-1 (ISO 5349-1 2001a). The severity of the risk is influenced by physical, biomechanical and individual factors. Monitoring all these variables has been considered impractical, thus the assessment is more or less based on the mean frequency-weighted vibration magnitude and the exposure duration during a working day (European Council 2002). Although, factors (such as, hand and arm positions and machine and tool conditions) contribute to the risk, they are normally not taken into account. These factors, which may increase or decrease the exposure dose and thus influence the risk, vary between different operators and work tasks, workplaces, between the machines and tools used and even periods of time (years, days, hours) (ISO 5349-1 2001a, Griffin 1997).

Several reports from other fields, for example chemical and biomechanical exposure, have demonstrated and quantified variations in exposure between both exposed operators and environmental conditions (Symanski et al. 2006, Liljelind 2002, Symanski et al 2000, Wahlström et al. *in press*). The importance of collecting not only valid and appropriate, exposure measurements, but also assessing the effects of key determinants (factors such as work tasks and practices, which increase or decrease the exposure) has been emphasized (Burstyn & Teschke 1999).

Variability in HAV has been previously described with respect to impact wrenches in two separate laboratory studies (McDowell et al. 2008, McDowell et al. 2009), and it has been concluded that machine, torque rating, operator as well as the tool–operator and tool–torque rating interactions significantly affect the measured vibration emissions. Similar findings have also been described in a laboratory “Round Robin” study, suggesting that the variability in vibration exposure assessments can be explained, to some extent, by factors such as auto balance unit, wheel and operator (Liljelind et al. 2009). This variability has a fundamental impact on the measurement strategies that should be adopted and may influence any proposed exposure–response relationships (Liljelind 2002, Rappaport et al.1995a, Rappaport et al. 1995b, Lin et al. 2005). Thus, an exposure assessment model for hand-arm transmitted vibration that takes into account exposure variability and factors (determinants of exposure) needs to be developed. A better knowledge of influencing and modifying factors will facilitate a better understanding of how the impact of tool or machine use is associated with the onset and development of vibration-induced injuries. In addition, knowledge of determinants could

lead to improvements in working conditions and providing objective reasons for introducing appropriate preventive measures in workplaces.

The aims of this study were to from two experiments (‘work posture’ and ‘wheel wear’) determine the equivalent hand-arm-weighted acceleration (m/s^2) of hand-arm vibrations in two work postures when using grinders, and to acquire (from repeated measurements) estimates of the variance components of factors that may affect the vibration exposure, i.e. grinding wheel, grinding machine and operator.

Material and methods

Study group

Two different simulated work tasks were simulated, in both of which 10 experienced male operators participated. In the “work posture” simulated work task the operators’ mean age was 43 years (range 36-53), mean height was 178 cm (range 166-188), and mean weight 80 kg (range 72-90). Seven other experienced male operators plus three who participated in the first task, were involved in the simulated work task “wheel wear”, and the mean age was 41 (range 27-53), mean height was 178 cm (range 168-190), and mean weight 83 kg (range 72-100). Height, weight and age were not used to model the exposure variability, since these variables are included in the effect of the operator.

Measurements

The data from both experiments were collected during a period of three weeks (March-April 2008). In both experiments, the same two grinders were used, both Atlas Copco GTG-20 (year of production 1999, 12000 rpm, equipped with an auto balance unit, 1.8 kg, 2.1 kW) and compressed air driven with a stated vibration value of <2.5 m/s^2 . The grinding test was undertaken on weld puddles of mild steel on a piece of mild steel. The brand of wheel was the Lamellar Flap Disc (Lukas SLT Flex125) ordered from the supplier, and the diameter of the wheel for the grinder was 125 mm (5").

Vibration measurements were collected according to the standard ISO 5349-1 (2001a) and the measurements sites were at the throttle handle, in accordance with ISO5349-2 (2001b). Neither of the grinders used in this study were equipped with a secondary support handle. The vibrations were measured with an accelerometer (Dytran 3053 B2) connected to an HVM 100 (Larsen & Davis). Just before and after the three weeks visit at the workplace where the two experiments were performed, the measuring equipment was calibrated with an accelerometer

calibrator (Brüel & Kjaer 4294) to ensure that no error had occurred during the performance of the experiments. No remounting of the transducers was undertaken during the experiments. The three perpendicular directions x, y and z were combined to calculate the vector sum. The vibration measure, calculated from the acquired data is the equivalent hand-arm-weighted acceleration (m/s^2) averaged over 1 min, hereafter referred to as the 'vibration value'.

Experimental design

<u>Work posture</u>

The work task consisted of a one-minute grinding activity in two different postures: horizontally at a work bench with a height of 105 cm, referred to as 'low', and, standing upright with elevated arms. The position with elevated arms was adjusted for each operator so that they started the grinding operation at approximately head height; this task is referred to as 'high' (Figure 1). The work task proceeded as follows: (1) using a new wheel, the operator started grinding at the work bench; (2) the operator moved to the wall and continued to grind at his head height using the same grinder and wheel; (3) the operator changed the wheel and performed the grinding task at head height on the wall with the same grinder; (4) the operator used the same wheel and grinder and performed the grinding task at the work bench (Figure 2a). The whole sequence was repeated using the second grinder. Each individual grinding task within the sequence lasted for one minute, which corresponds to a measured vibration value. All the operators repeated this sequence at three occasions with one to seven days in between**,** and at the second occasion they started with the other grinder to avoid systematic effects of grinder order. Hence, 10 operators performed eight different task-combinations (2 grinders – 2 wheels – 2 work postures) three times, thus the total number of vibration measurements was 240.

<u>Wheel wear</u>

To be able to investigate the effect of wheel and wheel wear, this experiment does not include simultaneous shift in the work posture and replacement of the wheel. The work task consisted of a one-minute grinding task on the work bench. For each grinder two previously unused wheels were used in the test. With each wheel the operator performed two consecutive one-minute grinding tasks, i.e. two runs for each wheel, which correspond to two measured vibration values (Figure 2b). Hence, 10 operators performed eight different combinations (2 grinders – 2 wheels – 2 consecutive grinding minutes), thus the total number of vibration measurements was 80.

The Umeå University Ethics Committee approved the study (approval no. Dnr 07-161M).

Statistical analysis

Work posture

All of the following statistical procedures were performed using the Statistical Package for the Social Sciences, SPSS (PASW) version 18.0 (SPSS Inc., Chicago, IL, USA). The significance level was set to 0.05.

To investigate the effect of work posture and to estimate the random effects associated with operator, grinder, wheel, occasion (work task sequence 1-4 described in section *Experimental design*, Work posture above) and the error term (residual), linear mixed effects model (REML) was used. The random effects are assumed to independent and normally distributed with a mean of zero. The form of the model used here was:

$$X_{ijklm} = \mu + \alpha_i + B_j + \chi_k + \delta_{l(ikm)} + \varphi_{m(i)} + \varepsilon_{ijklm} \qquad \text{(Equation 1)}$$

where X_{ijklm} represents the exposure value of the *i*-th operator assuming the *j*-th work posture at the *m*-th occasion, with the *k*-th grinder and the *l*-th wheel. Here, μ, α_i, β_j, χ_k, $\delta_{l(ikm)}$, $\varphi_{m(i)}$ and ε_{ijklm} represent the random effect of the *i*-th operator, the fixed effect of the *j*-th work posture, the random effect of the *k*-th grinder, the random effect of the *l*-th wheel within the *i*-th operator, the *k*-th grinder and the *m*-th occasion, the random effect of the *m*-th occasion within the *i*-th operator and the error term, respectively. Note, initially all interaction effects were included in the model but their estimated variance components were zero in all cases, so they were omitted from the model formulation (equation 1) and the results.
Statistical analysis was also separately done for each operator by using reduced models, where the operator effect and index *i* were excluded in the equation1. The results are commented upon in the result section.

Wheel wear

Linear random effects model (REML) was also used to evaluate the impact of operator, grinder, wheel, and the error term (among other things run), and the model used in this case was:

$$X_{iklm} = \mu + \alpha_i + \chi_k + (\alpha\chi)_{ik} + \delta_{l(ik)} + \varepsilon_{iklm} \qquad \text{(Equation 2)}$$

where X_{iklm} represents the exposure value of the i-th operator at the m-th run, with the k-th grinder and the l-th wheel. Here, $(\alpha\chi)_{ik}$ is the effect of the interaction between operator and grinder, and $\delta_{l(ik)}$ is the random effect of the l-th wheel within the i-th operator and the k-th grinder. The random effects are assumed to independent and normally distributed with a mean of zero. Also here, initially all interaction effects were included in the model but their estimated variance components were zero in all cases, so they were omitted from the model formulation (equation 2) and the results.

The goodness of fit of the models was evaluated by investigating the residuals and no strong deviations from the normal distribution were found.

In the 'Wheel wear' experiment the vibration value from the two consecutive runs (run 1 and run 2) was compared. The purpose was to evaluate if an unused wheel will change and influence the measured vibration value the first two minutes of usage. For each grinder a repeated analysis of variance was used with run and wheel as within-operator factors.

Results

The overall result from the two simulated work tasks showed that the average vibration value was approximately 3.2 m/s^2. The total variance (σ^2) was approximately 0.55, which corresponds to a standard deviation (σ) of 0.74 m/s^2. This means that the approximate prediction interval (Tamhane & Dunlop, 1999) (defined as including 95 % of the population, i.e. plus and minus two standard deviations (+/-1.5 m/s^2)) is 1.7 to 4.7 m/s^2.

Work posture

The vibration values recorded for the two grinders in the two different work postures are shown in Table 1. The average vibration values assessed when the task was performed at

work bench height (low) and at head height (high) were 3.2 m/s^2 and 3.3 m/s^2, respectively. There was no statistically significant difference in vibration values between the two work postures, p=0.4 (equation 1), Table 2. This can also be seen in Figure 3 for both grinders, where each data point represents the mean of two wheels that had been operated in the high and low postures, respectively. Since each operator repeated the task at three occasions, three data points for each posture are presented in the figure. No obvious overall pattern or structure based on work posture can be observed in the data.

Operator and grinder together explained only 12% of the exposure variability and both variance components were not statistical significant, while grinding wheel explained 47% and 41 % of the variability remained unexplained in the residual and both variance components were statistical significant (Table 2). No effect of 'occasion' was seen in the statistical analysis; interactions were included in the statistical model but did not explain any variability. Furthermore, the same statistical analysis based on each individual operator identified no significant effect of work posture, while a slightly larger effect of the grinder than at group level (shown in Table 2) was found for one operator (data not shown). For eight of the ten operators, approximately 40% or more of the variance could be explained by the between-wheel variance component (data not shown). For the other two operators, for whom there were small between-wheel variance components (<4% of the total variance), most of the variance (>70% of the total) was found in the residual i.e. unexplained variance. Each operator repeated the work task three times and the parameter 'occasion' explained 5 to 20% of the total variability, for five out of ten operators and nothing for the others.

Wheel wear

When the effect of grinding wheel wear was investigated as an average over all operators, the vibration values for grinder 1 for the first and second grinding minute were 3.4 and 2.9 m/s^2, respectively, and 3.1 and 2.9 m/s^2 for grinder 2. For grinder 1 the average vibration value for the first grinding minute was significantly higher (p=0.04) than the value for the second grinding minute (Table 3), based on the mean of the two wheels used in the task. This was consistent for eight out of 10 operators, Figure 4. Looking at each wheel separately (Table 3), the vibration value was higher for the first minute than for the second minute. This was also observed for one of the wheels for grinder 2.

In the estimation of variance distribution, 37% of the variability was significantly associated with the wheel while only a minor part of the variability (8%) was non-significantly associated with operator, and 37% remained unexplained (Table 4). The residual was

statistically significant and represents among other things, the effect of run. No variability was explained by the between-grinder variance component, but we found an interaction between grinder and operator, which represented 18% of the total variability. The interaction effect is not significant and if excluded the effect of operator increases but still the not significant (data not shown).

Discussion

The vibration values found for the grinders in this study are in the range recorded previously (Databases for Vibration Machines 2010), but higher than the by the manufacturer stated vibration value of <2.5 m/s^2 for this kind of grinders.

The overall average measured vibration value of the grinders examined was approximately 3.2 m/s^2. An operator would be allowed to operate a grinder for 4.5 hours, based on a daily 8-h reference period and the action level (2.5 m/s^2) specified in the European vibration directive (European Council, 2002). However, for 95% of the population, the interval of tolerance defined above produces vibration values between 1.7 and 4.7 m/s^2, which affect the uncertainty in the risk assessment. Hence, taking the uncertainty into account, an operator could be allowed to run the grinder for between 2.3 and more than 8 hours during a workday without exceeding the action level. At the individual level, giving any guidelines on “safe use” or limiting the duration appears to be somewhat futile. On the other hand, at the group level, operators performing this type of work task will be at different risks of developing clinical symptoms depending on whether the “high” or “low” end of the vibration value interval is considered. However, Burström et al. (2010) showed in their follow-up study of welders’ in a heavy engineering production workshop a daily mean value of 32 minutes (subjective assessment) with a standard deviation of 42 minutes for using grinders.

The design of this study allows us to closely examine the sources of this estimated variability. Work posture, in terms of elevated arms, did not affect the assessed vibration value and this was consistent for all ten operators (Figure 3). However, since the exposure time was short (1min), fatigue of the muscles in the shoulder was not likely to occur. Nevertheless, from a risk assessment point of view it is also important to assess risks other than vibration exposure, since workers exposed to hand-arm vibrations are often exposed to biomechanical risk factors (Wahlström et al. 2008, Bovenzi et al. 2005, Bovenzi et al. 1991, Armstrong et al. 2002). Elevated arms, the work task may be associated with a higher load on the muscles and

tendons of the arms and shoulders. It is well known that work with arms elevated to a high level is a risk factor for neuromuscular symptoms and disorders of the neck and shoulders (Svendsen et al. 2004, Silverstein et al. 2008). Standard work bench position is, however, believed to be the more common position for grinding operations. At the present work site preliminary and unpublished results (n=6), from direct measurements of upper arm postures and movements were recorded from workers performing grinding operations on a daily basis, showed that the upper arm was elevated >60 degrees about 8% of the working day.

All operators repeated each work posture task three times and the parameter ‘occasion’ explained only a negligible part of the variability in five of ten participating operators (data not shown) and thus, no training effect was observed. The operators, all experienced workers for whom grinding was a common work task, performed the repeated task in a very similar manner according to non-systematic observations. This observation is also supported by the results (Tables 2 and 4), in which the between-operator variance component explains only 8 and 10% of the total variance. However, the results from the wheel wear experiment indicate an interaction effect between grinder and operator corresponding to 18% of the total variability (Table 4). This was not seen in the work posture experiment and therefore we are not sure if it is a real effect or if it hidden by the design of the work posture experiment. Hence, there was no effect of the grinding machine, but the interaction effect was associated with the operator indicating that the effect of the grinder was not equal for all ten operators. We did not interview the operators about their opinion of the grinding machines or the performance of the task, but unsolicited comments that “one of the grinders was better than the other ” in terms of less vibration and a colder handle, were expressed by some of the subjects. Recently McDowell and colleagues, published two papers containing data from which the variance components can be calculated (McDowell et al. 2008, McDowell et al.2009). As in our study, the operator only explained a minor part (approx. 0-7%) of the variability. McDowell also found an interaction between operator and tool explaining approximately 10% of the variability, closely mirroring our results. In contrast, however, most of the variability (approximately 80-90%) was found in the machine components, while in our study the component machine (grinder) explained no more than 2% of the variability (Tables 2 and 4). One reason for this discrepancy is that different types of machines were used, i.e. an impact wrench compared to a rotary machine with an auto balance unit. These machine differences in the variance distribution need to be investigated further.

In our study approximately 40-50% of the variability in the data could be significantly linked to differences between grinding wheels (Tables 2 and 4). However, in the work posture evaluation, for two of the operators, almost no variability was found in the between-wheel variance component and the major part of the variability was allocated to the residual (data not shown). The reason for this finding cannot be evaluated in this study. However, one may speculate that, for example, the operators mounted the wheels in a similar way, the specific wheels they used had similar physical characteristics or this happened by pure chance. The variance in the residual is derived from factors not specified in the design, and thus not included in the model.

In a similar designed experiment as our wheel wear experiment, Liljelind et al (2009) found in their study with one grinding machine and repeated measurements using grinding wheels, that approximately 20% of the estimated variability was associated with the between-wheel variability. However there were some differences in the design of their study: the wheels used were grinding discs for metal, only one grinder was used and this grinder was sent to seven different laboratories where three operators at each laboratory performed grinding tasks with five wheels from the same batch. In addition, the transducer was remounted before each repeat. Thus other factors might explain the estimated variability. In the same study four different makes of grinders were used in the same grinding experiment but with no repetition. In this latter experiment, the between-wheel variance component explained 30% or more of the variability in the vibration value. Thus, even though the experimental designs differed, a considerable portion of the variability in vibration emissions from angle grinders seems to arise from the grinding wheels.

In the evaluation of the wheel wear (Table 3), the average vibration value for the first grinding minute was significantly higher ($p=0.04$) than the value for the second grinding minute for grinder 1. This was also the case for grinder 2 for one of the wheels but the difference was not significant. An unused disc has inherent roughness, which is reduced during use. The vibrations resulting from this roughness are normally balanced by the auto-balance unit attached to the grinding machine. In this case at least one of the grinders seems to have been unable to compensate for these wheel-associated vibrations. It is possible that the auto-balance unit was worn out. As mentioned earlier, unsolicited comments about the grinders suggested that one was better than the other.

The variance components associated with the wheel and the residual explain an almost equal amount of the variation; in total this accounts for most of the variability in the assessed vibration values (Table 2 and 4). The residual represents, among other things, e.g within-operator grip force in the work posture experiment and the effect of run (first and second grinding minute) in the wheel wear experiment as well as factors such as measurement error. How much of the residual that is represented by each component cannot be determined from the data.

From our results it can be concluded that in order to increase the precision of the mean of the assessed vibration exposure, it is important to increase the number of wheels used by the same grinder and operator. However, there are limitations associated with our study. We only included two grinders of the same make and model, both pneumatic and equipped with an auto balance unit, and only one brand of wheel was used and one selected work task i.e. grinding on weld puddles. Also the design of the experiments (fixed sequence of tasks) might have consequences for the generalization of the results. Thus, the results from our study cannot be generalised to other models, makes and sizes of grinding machine or other work postures. On the other hand, it is reasonable to believe that the exposure variability would be even greater if we included other makes of grinders or wheels or included operators undertaking other kinds of work tasks. Few studies have *simultaneously* examined several sources of exposure variability in work tasks in the HAV research field; by doing so further account could be taken of exposure variability in risk assessment. In order to evaluate whether this variance component pattern is conclusive, more studies are needed. The variability in the vibration value due to type of grinder, size of the grinding wheel and different types of grinding wheels mounted on different grinders is unknown and such studies are warranted. Still, the unexplained variability is of the same magnitude as that found between individual wheels and must be investigated further.

Conclusions

There is a considerable variability in vibration values, which affects risk assessments at both the group and individual level. Work posture during grinding operations does not appear to affect the hand-arm vibration value. The impact from various grinding wheels of the same type had the greatest influence on the variability. However, 40% of the estimated variance in the current study remained unexplained.

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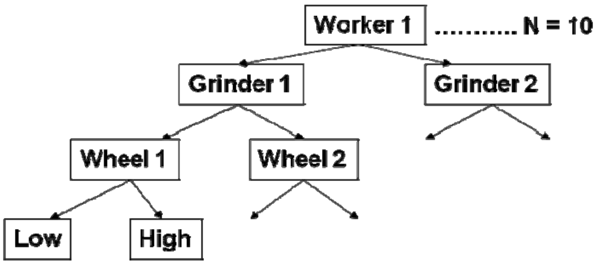
Figure 1. Illustration of the two different work postures investigated in this study: low (to the left) and high (to the right).

Figure 2. Design of the experiments

a) Work posture.

For each worker the sequence was repeated at three occasions.



b) Wheel wear.

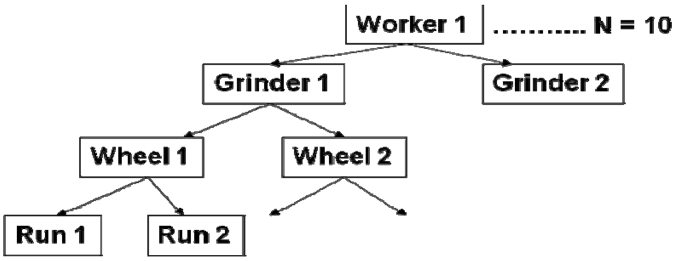
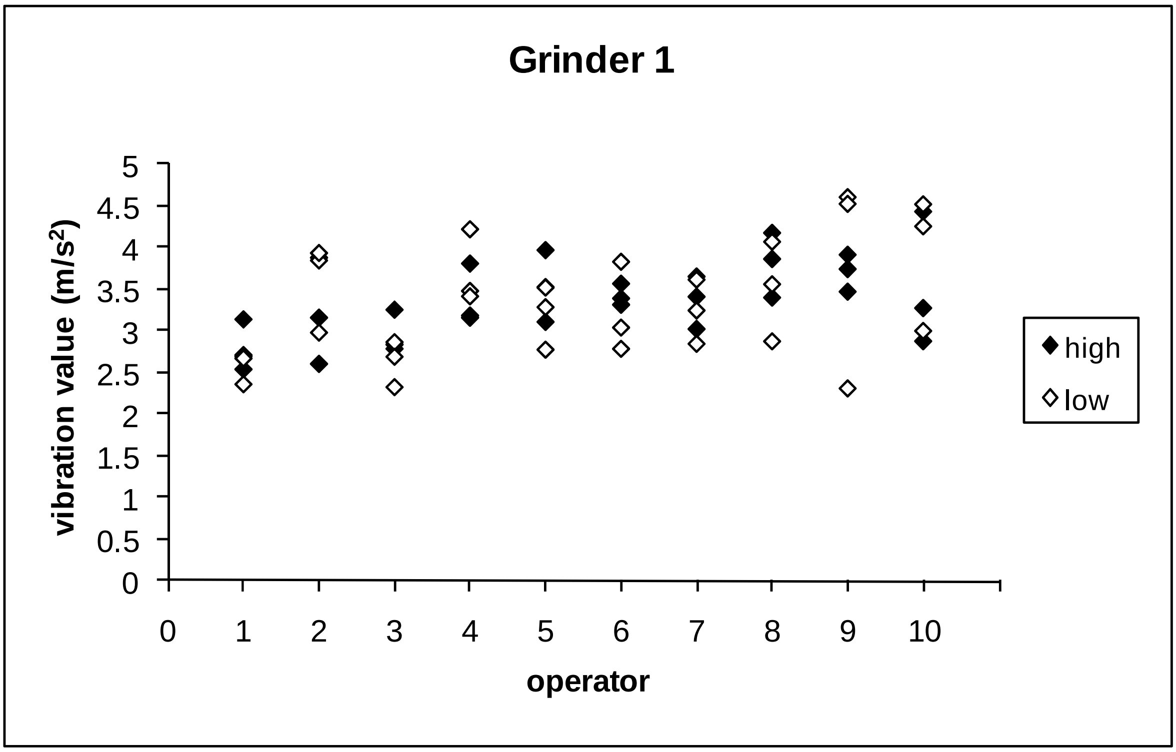


Figure 3. **Work posture and vibration values for each grinder**

The equivalent hand-arm-weighted acceleration (vibration value) for each operator performing the work task at the bench (low) and with arms elevated to head height (high) with grinder 1 (upper panel) and grinder 2 (lower panel), respectively. The vibration value is the mean from using two wheels and this was repeated three times i.e. three data points are presented in the figures for both high and low postures.



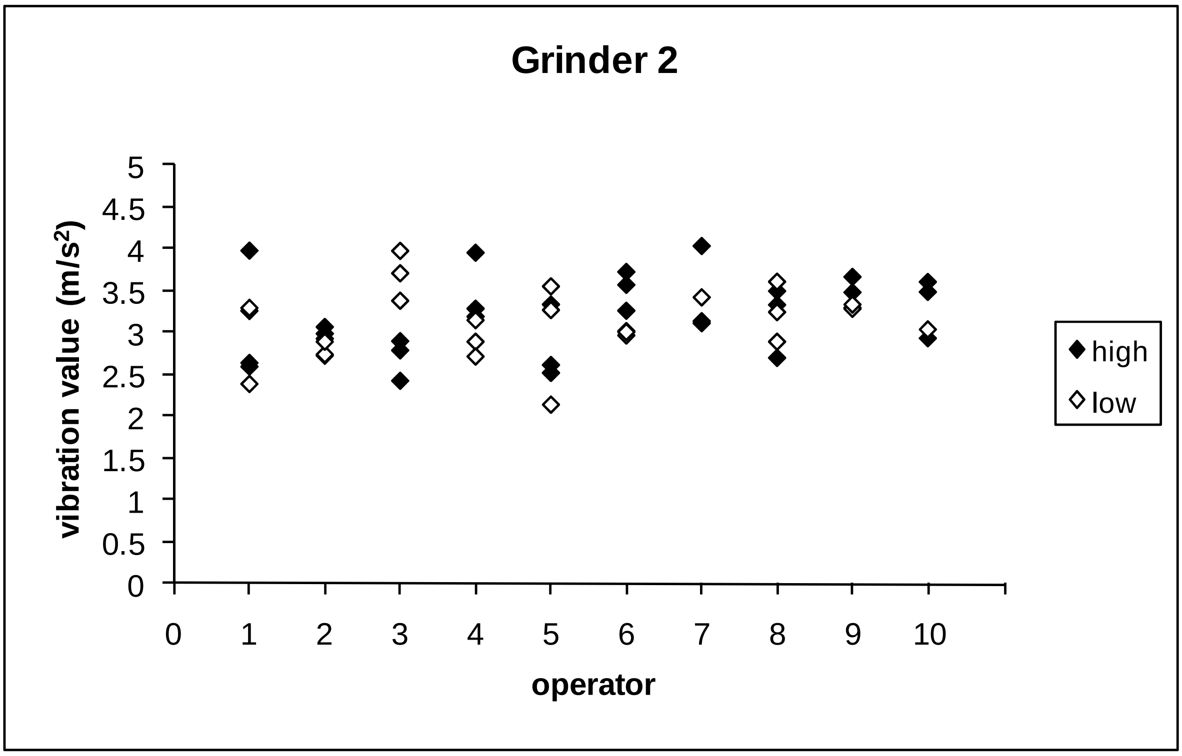
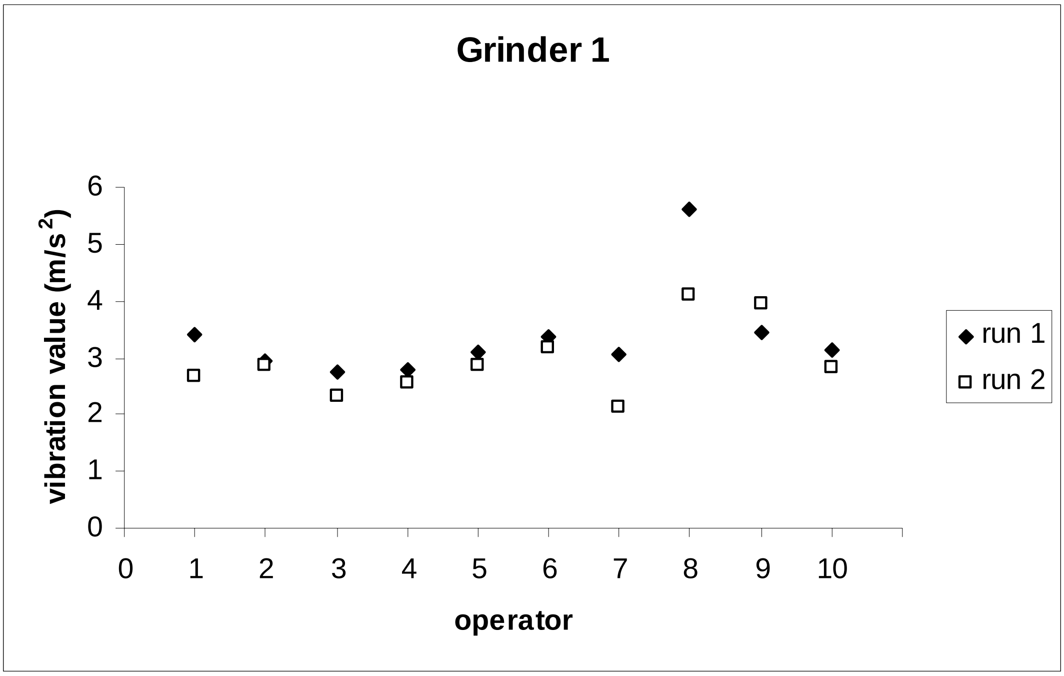


Figure 4. **Wheel wear and vibration values for each grinder**

The mean equivalent hand-arm-weighted acceleration (vibration value) for each operator running two wheels in two consecutive one-minute grinding tasks, with two different grinders (1 and 2). Run 1 equals the mean vibration value for wheels 1 and 2 for the first minute, and run 2 equals the mean vibration value of wheels 1 and 2 for the second minute.



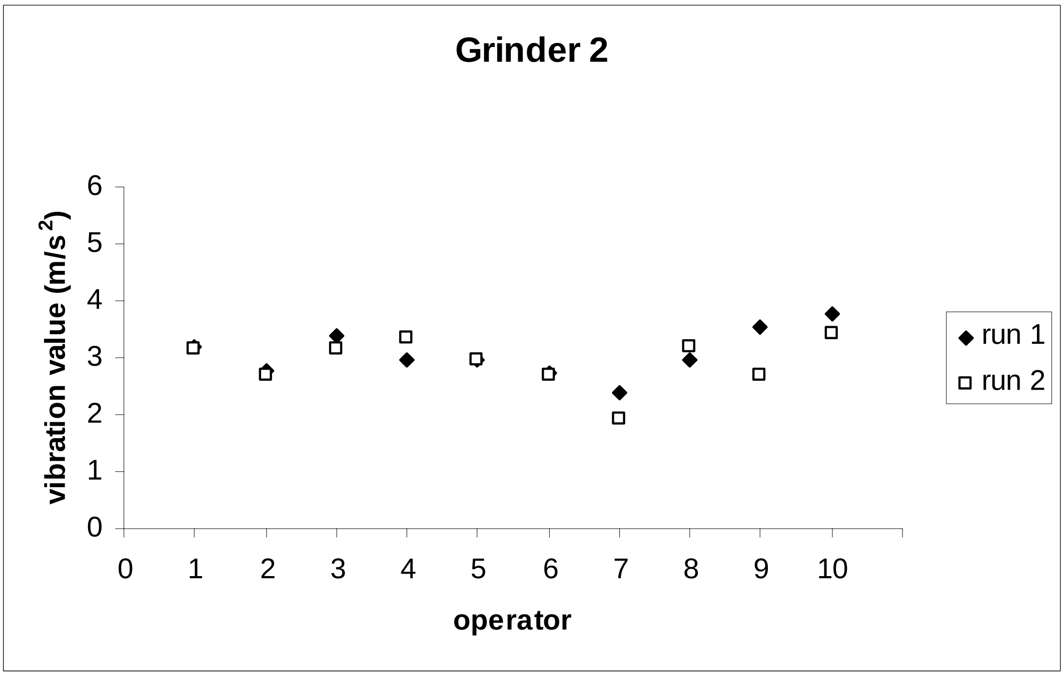


Table 1. **Work posture and vibration values**

The equivalent hand-arm-weighted acceleration (vibration value), arithmetic mean (AM), standard deviation (SD) and max-min (within brackets), assessed from two grinders, and as an average of both grinders operated at work bench height (low) and with arms elevated to head height (high). Ten operators repeatedly performed the grinding task with two grinders.

	Vibration value (m/s^2) AM ± SD (max-min)		
Work posture	high	low	Mean
Grinder 1	3.4±0.74	3.3±0.88	3.4±0.80
	(2.3-5.8)	(2.1-5.7)	
Grinder 2	3.2±0.68	3.1±0.68	3.2±0.65
	(2.2-5.2)	(1.9-4.7)	
Mean	3.3±0.71	3.2±0.76	3.3±0.74

Table 2. **Work posture and exposure variability**

Parameters estimated from the linear mixed effect model of the equivalent hand-arm-weighted acceleration (vibration value) after one minute grinding in two different postures, based on equation 1. Ten operators repeatedly performed the grinding task with two grinders. The percentage of the total variance is given in italics for each of the variance components.

Parameters	**Fixed effect** (95% CI / p-value)*	**Variance component** (95% CI / p-value)*
Work posture, high or low	0.056 (-0.067 – 0.178 / 0.369)	-
Between operator variance component		0.053 (0.012 – 0.231 / 0.18) *9.6%*
Between grinder variance component		0.012 (0.000 – 0.821 / 0.645) *2.2%*
Between wheel variance component		0.259 (0.174 – 0.386 / 0.000) *46.8%*
Residual		0.229 (0.178 – 0.296 / 0.000) *41.4%*
Total variance		0.553

* 95%-confidence interval and p-value

Table 3. **Wheel wear and vibration values**

Mean equivalent hand-arm-weighted acceleration (vibration values) assessed for the two grinders. For each grinder two wheels were used and ten operators performed the grinding task twice consecutively with each wheel (runs 1 and 2). Run 1 and run 2 correspond to the first and second minute grinding with the wheel, respectively.

	Vibration value (m/s^2) AM±SD (max-min)		
Grinder : wheel	**Run 1**	**Run 2**	**Mean**
1 : 1	3.4±1.3	2.9±0.76	3.2±1.1
	(2.6-6.8)	(1.7-4.2)	
1 : 2	3.3±0.56	3.0±0.71	3.1±0.64
	(2.7-4.4)	(2.2-4.0)	
2 : 1	3.1±0.64	2.8±0.71	2.9±0.67
	(2.1-4.0)	(1.6-3.9)	
2 : 2	3.1±0.45	3.1±0.62	3.1±0.53
	(2.5-3.6)	(2.3-4.0)	
1 : 1 & 2	3.4±0.95*	2.9±0.72	3.2±0.86
2 : 1 & 2	3.1±0.54	2.9±0.67	3.0±0.60
Mean	3.2±0.78	2.9±0.68	3.1±0.74

* $p<0.05$, when comparing run 1 with run 2 for both wheels and grinder 1.

SD = standard deviation, AM = arithmetic mean

Table 4. **Wheel wear and exposure variability**

Parameters estimated from the linear random effect model for the vibration value after two consecutive repeated one-minute grinding tests with each of the two wheels, based on equation 2. Ten operators performed the grinding test with two different grinders. The percentage of the total variance is given in italics for each of the variance components.

Parameters	**Variance component** (95% CI / p-value)*
Between operator variance component	0.047 (0.001 – 3.041 / 0.638) *8.4%*
Between grinder variance component	0 (-------)
Between wheel variance component	0.204 (0.078 – 0.532 / 0.041) *36.6%*
Interaction operator-grinder component	0.100 (0.010 – 1.103 / 0.409) *17.9%*
Residual	0.207 (0.133 – 0.320 / 0.000) *37.1%*
Total variance	0.558

* 95%-confidence interval and p-value