

Original Article

Hand-Arm Vibration Exposure in Rock Drill Workers: A Comparison between Measurements with Hand-Attached and Tool-Attached Accelerometers

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Abstract

Objectives: To assess the hazard of tool vibrations, we need valid exposure measurements. The use of hand-attached accelerometers (vibration sensors) to measure hand-arm vibrations (HAVs) has become a popular approach. However, according to International Standard ISO 5349-2, the preferred attachment of accelerometers is at the tool handle. We compared measures of HAV between hand- and tool-attached accelerometers in rock drilling.

Methods: We measured HAV in five rock drillers using jackleg drills in normal working operations with simultaneous measures of both hand-attached and tool-attached accelerometers. Five to seven measurement cycles of 15 s were executed on each worker, resulting in a total of 29 measurement cycles. To identify possible differences in working technique, we recorded videos of tool handle hand-grips during drilling.

Results: There was a significant difference (9.5 m s^{-2} ; $P \leq 0.05$) in vibration magnitudes measured by the tool-attached accelerometers compared with the hand-attached accelerometers. The hand-attached accelerometer showed a lower vibration magnitude for all workers (range of difference: 2.3–14.6). The variation between the two accelerometer attachments was larger between workers than within workers (ICC = 0.68).

Conclusions: For measurements of HAV from jackleg drills, the use of hand-attached accelerometers may cause a lower recorded vibration level compared with tool-attached accelerometers. This difference is likely to vary depending on how workers grip the tool handle, and a misclassification of exposure will occur if workers grip the tool handle in a way that makes the accelerometer lose contact

What's Important About This Paper

This study is important because it shows that the choice of accelerometer placement affects the measurement result. The working technique, specifically the individual handgrips used by workers, is an important factor to consider when planning measurements of hand-arm vibrations in the workplace. This study also reveals a potential for exposure reduction among rock drillers by altering how the workers grip a tool handle during drilling.

with the vibrating surface. Individual differences in how workers grip the tool handles should be considered when assessing HAV.

Keywords: accelerometer; exposure measurement; hand-arm vibration; hand-guided tools; handheld; hand-transmitted vibration; HAVS; rock drills

Introduction

High levels of exposure to hand-arm vibrations (HAVs) from handheld or hand-guided rock drills (Bovenzi *et al.*, 1994; Griffin *et al.*, 2003; Phillips *et al.*, 2007) are reported to be associated with negative health effects, and particularly hand-arm vibration syndrome (HAVS) (Pelmear and Taylor, 1994; Pelmeare, 2003). In order to identify workers at risk and effectively implement risk reducing actions it is important to use valid exposure assessments when investigating workers handling these tools.

For risk assessment, it is necessary to evaluate the vibration exposure based on measurements of several physical variables: vibration magnitude, vibration frequency, vibration direction, and exposure duration (Griffin, 1997). The standardized methods ISO 5349:2001 parts 1 and 2 (International Organization for Standardization, 2001) are adopted worldwide. In Norwegian legislation, the methods described in the standards are mandatory when assessing compliance with occupational exposure levels.

ISO 5349:2001 part 1 describes a method to establish daily exposure action values (EAVs) and exposure limit values (ELVs). According to this method, the vibration energy is measured as acceleration in meters per second squared ($m\ s^{-2}$) expressed as the root mean square (RMS). The vibration exposure is calculated as a time weighted average over an 8-h working day. ISO 5349 part 2 describes a method for measurement in the workplace. The method for exposure measurements described in the standard is a task-based strategy, which relies heavily on the professional judgment of the measurement personnel. They must identify typical work processes, measure them under typical conditions, and estimate the effective exposure duration to different

levels of vibration during a typical workday. According to the standard, the preferred placement of the accelerometers is on the tool handle using a firm attachment with studded clamps or glue and the tool handle should be held in a firm grip by the operator during measurement. Hand-attached accelerometers are considered the inferior option because of the measurement uncertainty that a relatively loose hand attachment may cause.

However, as an alternative to tool-attached accelerometers, hand-attached accelerometers connected to personal vibration exposure meters (PVEMs) has gained popularity and a new international standard for such equipment (ISO 8041-2 *Measuring instrumentation—Personal vibration exposure meters*) is in the final stage before publication by ISO in 2021. The use of PVEM is a more efficient and practical method, especially when measuring exposure from several tools which are used by a worker during a workday.

In addition to employers and labor inspection authorities assessing compliance with EAVs and ELVs to protect workers at the workplace, the procedures in the ISO-standards are also frequently used by researchers assessing exposure in epidemiological studies of effects of vibration exposure. However, previous studies on rock drilling operators (Brammer, 1986; Van Niekerk, 2000; Bast-Pettersen *et al.*, 2017; Clemm *et al.*, 2020) indicate that the task-based measurement strategy may lead to imprecise estimations of daily vibration duration due to variation in work technique between workers. In these studies, the researchers observed that when operating jackleg drills (hand-guided rock drills supported on a pneumatic driven cylinder) many workers adjusted their handgrips and sporadically removed their hands from the tool handle during drilling. Such variation may reduce or eliminate the

transmission of vibration energy from the tool to the hand, something that would not be captured by a tool-attached device, which measure the vibration energy at the tool handle. Thus, it is important to observe if there are individual differences between workers in how they grip the tool handles on the tools they operate.

It has also been shown that in self-reports workers tend to overestimate the duration of their exposure to vibration (Van Niekerk, 2000; Palmer *et al.*, 2000). One of the factors contributing to this may be the intermittent nature of the vibration exposure. This bias can affect predictions in epidemiological research (Gerhardsson *et al.*, 2005) of long-term risk from HAV exposure and may lead to an underestimation of the health hazards of exposure to HAV.

Measurements with PVEMs with hand-attached accelerometers may be used as a supplemental method to the preferred method in the standard. With PVEMs it is possible to record the exposure continuously during a full work shift. Thus, reducing the problem with imprecise estimations of exposure duration. The method has been described in the literature (Peterson *et al.*, 2007) and laboratory tests of hand-attached accelerometers have shown that measurements of vibration magnitude with hand-attached accelerometers give similar results as with the tool-attached accelerometers (Xu *et al.*, 2014). However, the setup and the predefined variables in a laboratory study are not necessarily representative of the variables acting on a worker in a real working situation. It is reasonable to assume that individual differences in working technique, such as variations in duration of contact and area of contact between hand and tool can lead to different results between the two measurement approaches. To our knowledge, comparisons between hand-attached accelerometers and tool-attached accelerometers to measure vibration exposure among rock drillers in realistic working conditions have not been reported in the literature.

The aims of the present study are to compare the measured vibration magnitude from hand-attached accelerometers and tool-attached accelerometers in a quasi-experimental setting of rock drilling; and to observe possible variations in how the workers gripped around the tool handles.

With this study, we want to contribute to better exposure assessment of HAV for risk assessment and research.

Methods

Study population

We invited workers employed in a Norwegian construction company to participate in the study. Five

experienced workers who were selected based on accessibility on the planned days of measurements all agreed to participate. The mean age of the subjects was 48 years and the mean experience with jackleg drills were 15 years. The subjects were all right-handed. Their work normally included operations such as attaching bolts, metal mesh, or fences to the rock face to reduce the risk of landslides and falling rocks. This work involved rock drilling with jackleg drills. A total of 50 rock face stabilizers worked in the company.

Measurement setup

We carried out vibration measurements on rock drillers using jackleg drills in normal rock drill operations. A total of 29 measurement cycles of 15-s duration were performed with five to seven consecutive measurement cycles on each worker. The 15-s measurement duration was considered adequate to ensure uninterrupted drilling during each measurement cycle. The measurements were done simultaneously with one tool-attached accelerometer and one hand-attached accelerometer connected to the same vibration meter. Thus, 58 measurements were obtained and stored as pairwise recordings.

During the measurements, we asked each worker to drill a horizontal hole in a natural rock face with a jackleg drill. This is a typical work task for the workers, and they were not instructed in any way, on how to perform the task. All workers drilled holes in the same area in the same rock face using an Atlas Copco BBC16W jackleg drill, which was the most used rock drill in the department. According to the manufacturer, this rock drill has a vibration magnitude of 16.6 m s^{-2} , an impact frequency of 39 Hz, and a weight of 28.5 kg (Atlas Copco, 2017–2019). The drill rod used during the measurements had a length of 160 cm and a tapered chisel drill bit of 24 mm diameter.

A six-channel vibration meter, Svantek 106 (Svantek, Warszawa, Poland) with inputs for two accelerometers: Svantek SV105 (Svantek, Poland) was used. The accelerometers were of the triaxial accelerometer type which measure in three axes simultaneously (X, Y, and Z axes). The sum RMS value from the three axes was calculated by the software program Supervisor (Svantek, Warszawa, Poland). One accelerometer was attached firmly to the handle of the tool by four layers of heavy-duty tape. The attachment was checked by applying manual pressure in all directions, ensuring no additional movement between handle and accelerometer during drilling could be possible. The accelerometer was attached with the X-axis aligned with the drill rod (stroke direction of the rock drill) The other accelerometer was attached to the palm of the hand by an integrated adjustable rubber band

(Fig. 1). The accelerometers were integrated in hand adapters similar in size and shape to the accelerometer that was used in a laboratory study reported by *Xu et al.* (2014) and referred to as a type 1 hand adapter. The workers used ordinary working gloves which they put on after the accelerometer was attached in the palm of the hand. The accelerometers were of a piezo-capacitive type, which are not prone to DC-shift. A frequency analysis of 1/3 octave frequencies (range 1–1400 Hz) was done to check for artifacts in the time domain. The vibration meter fulfilled the requirements of ISO 8041-1:2017 (International Organization for Standardization, 2017) and was calibrated according to protocol.

Observations of handgrip

In a separate session after the measurement session, the workers were observed to see if visible differences in handgrip during drilling could be observed. To assess for any visible positional changes of the hand, close-up videos of the handgrip on the handle during drilling

were recorded and viewed in slow motion. During video recording the recording angle was aligned with the axis of the tool handles and the workers removed their glove so that the position of the hand against the tool handle could be inspected. Videos both with and without hand-attached accelerometers were recorded to visualize the contact between the hand and the tool handle. The work tasks performed without working gloves that were recorded on video were not part of the statistical analyses because the workers always work with gloves; therefore, such measurements would not have been representative of their ordinary way of working. Further, removing the working glove would increase friction between the accelerometer and the tool handle which could have an impact on the measurement results.

Statistical analysis

The mean, range, and standard deviation of the exposure variable ($m\ s^{-2}$) for each worker for both accelerometer placements were calculated. A visual inspection and



Figure 1. Work process (jackleg drilling) done for simultaneous measurements with tool-attached (upper right in picture) and hand-attached (lower right) accelerometers.

comparison of the residuals with a normality plot showed an almost perfect fit, thus a normal distribution of the data was assumed. Mixed-effect model with worker as random intercept and pairwise measurement differences between the two accelerometer placements as fixed effect were used to assess mean difference between hand and tool measurements for the workers. Because there were no missing data, the pairwise measurement difference could be used directly as a fixed effect. Based on this model, intraclass correlation was calculated, which gives a measure of the proportion of variability within and between workers for the repeated measurements.

The same mixed-effect model as described above but sorted by worker as random effect was used to assess mean difference between hand and tool measurements for each worker separately. Statistical analysis was performed using Stata 16 (StataCorp, College Station, TX, USA).

Ethics approval

The workers participation was voluntary, and the procedures did not pose any risk of negative health effects. The study was approved by the Ethical Research Committee of South-East Norway (approval number 2013/1031).

Results

Comparison of tool-attached and hand-attached accelerometers

For four out of the five workers there was a significant difference ($P < 0.05$) between the results from the

measurements on the tool handle and the results from measurements in the hand (Table 1).

The mean of all the measurements was 28.5 m s^{-2} (range between individuals: 21.9–34.4) for the tool-attached accelerometers and 19 m s^{-2} (range: 10.5–31.0) for the hand-attached accelerometers (Table 1). In mixed-effects models, the difference in results between the tool- and hand-attached accelerometers was significant ($P < 0.05$) (Table 2).

The variation between the two accelerometer attachments was larger between workers compared with within workers. Intraclass correlation was 0.68. Thus, the proportions of the total variation that is due to differences between workers were 68%.

The reduction in measured acceleration from the tool-attached accelerometers to the hand-attached accelerometers ranged from 8% in worker 1 to 49% in worker 3 (calculated from the coefficients in Table 1). The measurement results in the individual X, Y, and Z axes from the tool-attached accelerometers show a mean acceleration energy of 72% in X-axis, 12% in the Y-axis, and 16% in the Z-axis, and from the hand-attached accelerometers 40% in the X-axis, 19% in the Y-axis, and 41% in the Z-axis (Supplementary Table S1, available at *Annals of Work Exposures and Health* online). Standard deviations of the measurements with the tool-attached accelerometers were smaller in all three axes compared with the measurements with the hand-attached accelerometers (Table 3). During the measurements, all five workers kept their hand on the tool handle.

Table 1. Mean vibration magnitudes from simultaneous measurements on tool handle and in hand and mixed model sorted by worker.

Subjects	Accelerometer placement	N	Mean (m s ⁻² RMS)	Range (m s ⁻² RMS)	SD	Range of diff. between tool handle and hand	Mixed model ^a	Mixed model ^a		Mixed model ^a	
								Coefficient	Standard error	95% Confidence Int.	
Worker 1	Tool handle	5	27.5	25.3	32.2	2.8	Ref = 0	27.5	1.29	25.0	30.1
	Hand	5	25.2	22.6	31.0	3.6	-1.1	-3.7	-2.3	1.83	-5.91
Worker 2	Tool handle	7	25.8	21.9	29.3	2.8	Ref = 0	25.8	1.34	23.2	28.4
	Hand	7	19.2	18.2	27.2	4.6	-4	-9.1	-6.5	1.89	-10.3
Worker 3	Tool handle	5	29.8	28.5	32.1	1.4	Ref = 0	29.8	1.07	27.8	31.9
	Hand	5	15.2	10.5	19.5	3.5	-11.8	-18	-14.6	1.51	-17.60
Worker 4	Tool handle	5	30.1	28.6	32.0	1.5	Ref = 0	30.1	1.45	27.3	32.9
	Hand	5	18.8	11.6	25.1	4.9	-6.9	-18.3	-11.3	2.04	-15.3
Worker 5	Tool handle	7	29.8	27.9	34.4	2.2	Ref = 0	29.8	1.10	27.7	32.0
	Hand	7	17.2	13.3	24.1	3.8	-5.3	-15.2	-12.7	1.55	-15.7
All five workers	Tool handle	29	28.5	21.9	34.4	2.8	Ref = 0				
	Hand	29	19.0	10.5	31.0	5.0	-1.1	-18.3			

^aModel sorted by worker, with pairwise difference between tool handle and hand as fixed effect and worker as random effect.

Table 2. Mixed-effects model: difference in measurements on tool handle and in hand for all workers.

Difference	Coefficient	Standard error	95% Conf. interval	
Mean difference (_cons) ^a	9.50	1.99	5.60	13.4
Random-effects parameters	Estimate	Standard error	95% Conf. interval	
Constant	18.2	12.6	4.71	70.6
Residual	8.75	2.53	4.96	15.4
Intraclass correlation	ICC	Standard error	95% Conf. interval	
Proportion of total variance that is a between worker effect	0.68	0.17	0.32	0.90

^aModel with pairwise difference between tool handle and hand as fixed effect and worker as random effect.

Table 3. Mean vibration magnitudes from pairwise simultaneous measurements in individual axes.

Axis	Accelerometer placement	N ^a	Mean (m s ⁻² RMS)	Range (m s ⁻² RMS)		SD	Range of diff. between tool handle and hand	
X	Tool handle	24	24.3	19.7	29.6	2.3	Ref = 0	
	Hand	24	11	5.3	16.8	3.6	-7.8	-20.5
Y	Tool handle	24	9.6	7.1	13.2	1.7	Ref = 0	
	Hand	24	7.7	3.5	15.2	2.8	4.8	-8.4
Z	Tool handle	24	11.5	5.8	14.2	2.5	Ref = 0	
	Hand	24	11.1	5.3	16.8	3.3	7	-8.7

^aThe vibration level in the individual X, Y, and Z axes for worker 1 was unattainable because of a file saving error. Therefore, the mean levels are based on workers 2–5.

Observations of workers' handgrips during drilling

It was apparent that workers applied different handgrips. Three different types of grips were identified as typical:

1. Closed grip with palm of the hand and fingers flexed around the tool handle (Fig. 2, top). In this situation, the hand and fingers vibrate together with tool handle.
2. Fingers flexed around tool handle, but no contact between palm of hand and tool handle. In this situation, the fingers vibrate together with the tool handle. The worker was wearing a hand-attached accelerometer and it can be clearly seen in Fig. 2 (middle) and in the video (Supplementary Material, available at *Annals of Work Exposures and Health* online), that there is no contact between the accelerometer and the tool handle.
3. Open grip with slightly more extended fingers. In this situation, the tool handle vibrated within the hand, causing less transmission of vibrations to the fingers; see Fig. 2 (bottom).

Some workers reported (personal communication) that it was quite normal also to change handgrip during a drilling operation.

Discussion

We found a significant difference between the measurements with tool-attached and hand-attached accelerometers. The mean difference was 9.5 m s⁻². The mean vibration magnitude measured on the tool was 28.5 m s⁻² and measured in the hand, 19 m s⁻². Calculated as percentages of the mechanical energy ([m s⁻²]²), the reduction from tool-attached to hand-attached accelerometers ranged from 14% (worker 1) to 72% (worker 3). The variation in mean difference for each worker ranged from 2.3 to 14.6 m s⁻². The variation was much larger between the workers than within the workers, indicating that individual factors may play an important role in the measured differences. During the observations of handgrips during drilling operations, we found that different handgrips were used.



Figure 2. Type 1–3 hand grips (from top to bottom respectively). Top: closed grip with fingers and palm flexed around tool handle. Middle: semi-open grip with only fingers flexed around tool handle (no contact between tool handle and accelerometer). Bottom: open grip.

The measured vibration magnitudes were higher than the vibration level (16.6 m s^{-2}) reported by the producer. The most likely explanation is that the producer has used a different measurement setup. However, no information about measurement variables such as type of material being drilled, or diameter of drill bit was supplied by the producer. These are variables which typically has a great impact on the measurement results. Usually, the producer uses a standard method for laboratory measurement of hand-tools (ISO 28927-10:2011 *Handheld portable power tools—Test methods for evaluation of vibration emission—Part 10: Percussive drills, hammers, and breakers*) (International Organization for Standardization, 2011) where important variables which may have an effect on exposure are defined, with instructions on how they should be controlled in a laboratory setting.

The measurement results are in contrast to the findings in the laboratory study by Xu *et al.* (2014) where there was close agreement between the two accelerometer attachments. However, in that study the measurements were performed with a constant grip force of 30 N and push force of 80 N. This is a highly unlikely scenario in real life work, with workers of different strengths, sizes, and work habits. In our study, no

push force was used. That is because a jackleg drill is not operated with manual push force. The pneumatic driven jackleg that the rock drill is mounted to has a push force of up to 2000 N. Thus, there is no need to push manually. We did not measure grip force in our study. Individual differences in grip force may also have contributed to the measured differences. However, it is reasonable to assume that when workers use handgrips where the hand-attached accelerometer at times is not even in contact with the vibrating surface of the tool handle, there will be a great influence on the measurement results, independent of the grip force exerted.

The measurement results in the individual axes showed that for the tool-attached accelerometer the dominant exposure happened in the X-axis, corresponding to the stroke direction of the rock drill. For the hand-attached accelerometer, the dominant exposure was almost equally split between the X-axis and the Z-axis and the SD was larger, indicating a larger scattering of results. It is a reasonable assumption that this was caused by the workers changing the hand position in the sagittal plane on the tool handle. This supports a hypothesis that the difference in results between the tool-attached and hand-attached accelerometers is influenced by different ways of gripping the tool handle.

An interesting finding in our study was the identification of different types of individual handgrips that may be an explanation for the variations in mean differences between the measurement results from the two accelerometer attachments. This is a variation related to individual working technique which comes in addition to the intermittent hand contact described in the introduction. The differences between the handgrips were not obvious or easy to spot when looking on the workers operating the jackleg drills. However, the pictures and videos of the hands on the tool handles during drilling revealed that the workers did indeed have different handgrips. We observed three distinct grips which we believe are important to be aware of for interpretation of the results. The types of handgrip most likely had an impact on the measurements. In the type 1 handgrip the tool handle is held in a tight grip and the whole hand vibrates together with the tool handle. It is a reasonable assumption that in this situation there is a good agreement (small difference) between the measurements with the hand-attached and the tool-attached accelerometer. This firm grip is recommended in the measurement standard ISO 5349-2. However, as we observed this was not the only type of grip which was used during drilling. In the type 2 handgrip, only the fingers are folded around the tool handle. In this situation, the fingers vibrate together with the tool handle. However, as it can be seen in Fig. 2 (middle)

and in the video ([Supplementary Material](#), available at *Annals of Work Exposures and Health* online), a hand-attached accelerometer may lose contact with the tool handle. The accelerometer will still record vibrations because the whole hand is still vibrating from the contact of the fingers, but the accelerometer will measure a lower vibration than what is actually transmitted to the fingers. In the type 3 grip, the grip is open as can be seen in [Fig. 2](#) (bottom) so that the tool handle vibrates within the hand. In this situation, the hand and fingers are still exposed to the vibrations, but the hand and fingers does not move together with the tool handle. Thus, the vibration exposure is reduced. The accelerometer will only loosely be in contact with the tool handle and will therefore record less vibration. Whether it records less vibration compared with a situation with a type 2 grip is not known.

The following general hypothesis should be considered when studying HAV exposure from rock drilling:

- For grip type 1: HAV exposure is similar to the vibration magnitude at the tool handle. Measurements from tool-attached and hand-attached accelerometers are in good agreement. Thus, both approaches show a good approximation of the HAV exposure.
- For grip type 2: HAV exposure is similar to the vibration magnitude at the tool handle. Tool-attached accelerometers show a good approximation of the HAV exposure. Hand-attached accelerometers underestimate vibration exposure.
- For grip type 3: HAV exposure is reduced and not similar to the vibration magnitude at the tool handle. Measurements from tool-attached and hand-attached accelerometers are not in good agreement. To what extent the measurements from hand-attached accelerometers gives a better approximation of HAV exposure is not known.

This hypothesis can explain why the measurements on worker 1 and to some degree on worker 2 showed good agreement between the two accelerometer placements (mean difference of 2.3 and 6.5 m s^{-2}) while not so for workers 3, 4, and 5 (mean difference of 14.6, 11.2, and 12.7 m s^{-2}). A plausible explanation for this is that these workers used grip type 1, while the other workers used grip type 2 or 3.

A limitation of our study is that during the video recordings no measurement data were collected. The reason for this was that the working gloves which the workers always use in normal operation was removed to be able to see the position of the hands and fingers on the pictures and videos. Such data could have shown the direct effects on the measurements the different type of

handgrips had. More measurements on a larger population could have uncovered more individual working techniques which might also impact on which measurement approach is the most useful for a specific purpose. However, our data show a very clear pattern of lower measurement results when hand-attached accelerometers are used. The pictures and videos give plausible explanations for the measured differences. It is reasonable to assume that a lack of contact between the accelerometer and the vibrating surface will cause a reduction in measured vibration magnitude. To assess to what degree the observed type of handgrips (and possibly other type of handgrips) is influencing the measurement results a study with a laboratory setup is warranted.

A strength of this study is that the measurements and observations were done in a realistic working environment with the workers using their preferred working technique. There are to our knowledge no published studies comparing measurements with hand-attached and tool-attached accelerometers in realistic working conditions. The results show how important it is to always consider how different measurements in a real working situation can be, compared with a controlled laboratory study. One can easily overlook important variables.

The findings of our study are important because it shows that for exposure measurements of jackleg drilling, individual differences on how the workers grip a tool handle may change vibration exposure without the vibration meter being able to measure the change. The implications for epidemiological research could be that the standardized method causes an overestimation of cumulative exposure that comes as an addition to the already known difficulties with recall bias causing overestimation of exposure time ([Brammer, 1986](#); [Van Niekerk, 2000](#); [Palmer et al., 2000](#); [Gerhardsson et al., 2005](#)). However, using the hand-attached accelerometer approach might cause the opposite problem. Because if workers frequently use grip type 2, an underestimation of the HAV exposure may occur.

In our study, the workers did not remove their hands from the tool handle during drilling. A reason for this could be that the drilling operation on the days of measurement was split in relatively short cycles and was not as exhausting or uncomfortable as some ordinary workdays can be. Vibrations from jackleg drills are very high and for lasting drilling operations it can become uncomfortable for the workers because of acute health effects such as tingling and numbness ([Malchaire et al., 1998](#); [Bovenzi et al., 2004](#)). It is reasonable to assume that workers using jackleg drills will adapt to situations of high HAV

exposure by changing their work technique to relieve these uncomfortable short-term effects from vibration. These behaviors may also alter the long-term risk for HAVS on an individual level.

Our findings are relevant also to other exposure situations than rock drilling. Employers who want to check for compliance with EAV and ELV for HAV exposure in the workplace need to be aware of the implications individual working techniques may have. This can be illustrated by using the results from our study on an individual worker, as an example: A worker exposed to 19 m s^{-2} will reach the ELV (in most countries in the world the ELV is a daily vibration dose of $5 \text{ m s}^{-2} \text{ A8}$) in 33 min, while if the exposure is 28.5 m s^{-2} the ELV is reached in less than half the time: 15 min. This uncertainty will in many situations be unacceptable and make it hard to establish reasonable knowledge-based measures to reduce vibration in the workplace.

Some measurement devices have incorporated grip force measurement capabilities in hand-attached accelerometers. This may be an efficient way of measuring exposure duration during a full work shift. However, it would not be a useful procedure to measure full shift jackleg drilling with a type 2 grip because such a grip could wrongly be classified as a no-exposure situation exposure because there is no measurable grip force, even though the vibrations transmitted to the fingers can be very high.

Our findings may be relevant also for the use of other types of hand-guided power tools, such as grass cutters, vibro-plates, concrete vibrators, and demolition hammers. Further research on the effect of different handgrips on measurement results comparing the hand-attached and tool-attached measurement approach is needed. The observation that different handgrip types may modify the transmission of vibration to the hand is also an indication that preventive measures could be identified and that workers could be educated to reduce their exposure by adapting the grip to the task that is performed, minimizing the transmission of vibration to their hands during operation of the tool.

Conclusion

Measurement results with use of hand-attached accelerometers show a clear tendency of underestimating vibration exposures compared with measurements with the use of tool-attached accelerometers. One of the reasons for this is that workers often use a different grip compared with the recommendations in the measurement standard ISO-5349-2. Exposure assessments of HAV are likely to be affected by individual work technique.

The modifying factors related to type of handgrip should always be considered if planning to measure HAV exposure. These factors' potential for exposure reduction as a preventive measure against HAVS should also be considered in situations where the contact between tool and hand can be modified by the worker.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Disclaimer

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Conflict of interest

None declared.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author. Data are stored as deidentified participant data.

References

- Atlas Copco. (2017–2019) Technical specifications. Atlas Copco. Available at <https://www.atlascopco.com/en-uk/construction-equipment/products/handheld/rock-drills/pneumatic-rock-drills/bbc16w#!>. Accessed 14 January 2020.
- Bast-Pettersen R, Ulvestad B, Færden K *et al.* (2017) Tremor and hand-arm vibration syndrome (HAVS) in road maintenance workers. *Int Arch Occup Environ Health*; **90**: 93–106.
- Bovenzi M, Franzinelli A, Scattoni L *et al.* (1994) Hand-arm vibration syndrome among travertine workers: a follow up study. *Occup Environ Med*; **51**: 361–5.
- Bovenzi M, Welsh AJ, Griffin MJ. (2004) Acute effects of continuous and intermittent vibration on finger circulation. *Int Arch Occup Environ Health*; **77**: 255–63.
- Brammer AJ. (1986) Dose-response relationships for hand-transmitted vibration. *Scand J Work Environ Health*; **12**: 284–8.
- Clemm T, Færden K, Ulvestad B *et al.* (2020) Dose-response relationship between hand-arm vibration exposure and vibrotactile thresholds among roadworkers. *Occup Environ Med*; **77**: 188–93.

- Gerhardsson L, Balogh I, Lambert PA *et al.* (2005) Vascular and nerve damage in workers exposed to vibrating tools. The importance of objective measurements of exposure time. *Appl Ergon*; **36**: 55–60.
- Griffin MJ. (1997) Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration. *Occup Environ Med*; **54**: 73–89.
- Griffin MJ, Bovenzi M, Nelson CM. (2003) Dose-response patterns for vibration-induced white finger. *Occup Environ Med*; **60**: 16–26.
- International Organization for Standardization. (2001) *ISO 5349-1 & 2:2001 Mechanical vibration—measurement and evaluation of human exposure to hand-transmitted vibration—Part 1: General requirements—Part 2: Practical guidance for measurement at the workplace*. Norway: Standard Online AS.
- International Organization for Standardization. (2011) *ISO 28927-10:2011 Hand-held portable power tools—test methods for evaluation of vibration emission—Part 10: Percussion drills, hammers and breakers*. Norway: Standard Online AS.
- International Organization for Standardization. (2017) *ISO 8041-1:2017 Human response to vibration—measuring instrumentation—Part 1: General purpose vibration meters*. Norway: Standard Online AS.
- Malchaire J, Rodriguez Diaz LS, Piette A *et al.* (1998) Neurological and functional effects of short-term exposure to hand-arm vibration. *Int Arch Occup Environ Health*; **71**: 270–6.
- Palmer KT, Haward B, Griffin MJ *et al.* (2000) Validity of self reported occupational exposures to hand transmitted and whole body vibration. *Occup Environ Med*; **57**: 237–41.
- Pelmear PL. (2003) The clinical assessment of hand-arm vibration syndrome. *Occup Med (Lond)*; **53**: 337–41.
- Pelmear PL, Taylor W. (1994) Hand-arm vibration syndrome. *J Fam Pract*; **38**: 180–5.
- Peterson DR, Brammer AJ, Cherniack MG. (2007) Exposure monitoring system for day-long vibration and palm force measurements. *Ind Ergon*; **38**: 676–86.
- Phillips JI, Heyns PS, Nelson G. (2007) Rock drills used in South African mines: a comparative study of noise and vibration levels. *Ann Occup Hyg*; **51**: 305–10.
- Van Niekerk JL. (2000) Human vibration levels in the South African mining industry. *SAIMM J*; **100**: 235–42.
- Xu XS, Dong RG, Welcome DE *et al.* (2014) An examination of the handheld adapter approach for measuring hand-transmitted vibration exposure. *Measurement*; **47**: 64–77.