OPEN ACCESS

Original research

Exposure-response relationship between hand-arm vibration exposure and vibrotactile thresholds among rock drill operators: a 4-year cohort study

Thomas Clemm [1], Lars-Kristian Lunde [2], Bente Ulvestad [1], Karl Færden [3], Karl-Christian Nordby [1]

► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/oemed-2022-108293).

[1]Department of Occupational Medicine and Epidemiology, STAMI, Oslo, Norway
[2]Unit for Systematic Reviews, STAMI, Oslo, Norway
[3]Department of Environmental and Occupational Medicine, Oslo University Hospital, Oslo, Norway

Correspondence to
Dr Thomas Clemm, Department of Occupational Medicine and Epidemiology, STAMI, 0363 Oslo, Norway; thomas.clemm@outlook.com

Received 16 February 2022
Accepted 22 May 2022

ABSTRACT

Objectives The risk of developing hand-arm vibration syndrome (HAVS) from occupational hand-arm vibration (HAV) exposure is traditionally determined by the onset of vascular symptoms (white fingers). However, changes in tactile sensibility at the fingertips is a clinical sign of HAVS which in most cases precedes vascular signs. We aimed to assess relationships between occupational HAV exposure and HAVS-related signs including vibration perception thresholds (VPT) and pegboard score on an individual level, using a longitudinal study design with follow-up tests.

Methods We followed-up 148 workers exposed to different HAV levels for 4 years, with health examinations including VPT tests and pegboard tests carried out at baseline, 2 years and 4 years. VPT testing included seven frequencies, from 8 to 500 Hz. Second and fifth finger on both hands were tested, thus a total of 28 tests on each subject. We investigated associations using linear mixed models and significance level at $p \leq 0.05$.

Results There was a significant exposure-response relationship on an individual level between HAV exposure from rock drills and VPT for 16 of 28 test frequencies. The highest rise (worsening) in VPT was found at the 500 Hz test frequency with 1.54 dB increased VPT per 10-fold increase in cumulative exposure. We found no deterioration in pegboard performance associated with HAV exposure among the participants.

Conclusions Risk predictions of HAVS may be based on exposure-response relationships between HAV exposure and VPT. The 500 Hz test frequency should be included in the VPT test protocols for early detection of signs related to reduced tactile sensibility.

WHAT IS ALREADY KNOWN ABOUT THIS SUBJECT?

⇒ Neurological signs of hand-arm vibration syndrome (HAVS) usually precede the vascular symptoms (white fingers).
⇒ Considering hand-arm vibration (HAV) exposed groups versus unexposed groups there is a clear relationship between HAV exposure and reduced tactile sensitivity measured as vibration perception thresholds (VPT). On an individual level there are only indications of a relationship.

WHAT ARE THE NEW FINDINGS?

⇒ We found a clear relationship on an individual level, between HAV exposure and VPT based on longitudinal data with follow-up VPT tests.
⇒ VPT at the 500 Hz test frequency is the most affected by HAV exposure, indicating that testing at this frequency is a suitable method to detect early changes in VPT.

HOW MIGHT THIS IMPACT ON POLICY OR CLINICAL PRACTICE IN THE FORESEEABLE FUTURE?

⇒ Future risk models for the prediction of HAVS should include quantitative tests of neurological signs using VPT as a measure.
⇒ Test protocols for VPT should include the 500 Hz test frequency to enable earlier detection of affected VPT.

INTRODUCTION

Manual work with vibrating tools can cause neurological sensory disorders, vascular disorders (white fingers) and pain in the hands. The condition is known as hand-arm vibration syndrome (HAVS).[1] Over the last decade there has been an increase in the number of vibration-exposed workers referred to occupational health departments in Norwegian hospitals due to HAVS-related symptoms.[2] In Sweden HAVS is the most common occupational disease according to AFA (Swedish insurance company for work-related injuries and disease).[3] HAVS is a complex disease, and the full pathophysiology is plausibly yet to be discovered.[4]

HAVS mainly affect nerves, causing symptoms such as reduced motor control, reduced sensibility to temperature and vibration and the digital capillaries, causing an abnormal constriction in response to cold. This causes the typical symptoms of white fingers with clear demarcation between affected and unaffected areas on the skin.

The different symptoms can occur separately, at the same time or at different stages in the development of the disease. The sensory nerve injuries are described as the most difficult to treat,[5–7] and at equal exposures these injuries typically appear with a latency period of one third compared with the latency period of the vascular injuries.[8] However, the most referenced risk assessment model (presented in an annex to ISO 5349–1[9]) is based on literature published from 1950 to 1980 which only assesses risk of vascular disorder. Despite this, the

Check for updates

To cite: Clemm T, Lunde L-K, Ulvestad B, *et al*. *Occup Environ Med* Epub ahead of print: [please include Day Month Year]. doi:10.1136/oemed-2022-108293

model is also used for risk predictions of neurological injuries. With the current knowledge that neurological symptoms usually precedes the vascular symptoms; it is important to address the neurological component of HAVS to be able to discover symptoms at an early stage.

There is no universal consensus on the diagnostic criteria for HAVS. Updated criteria have been proposed by Pool *et al*[10] as a step towards consensus. They proposed quantitative sensory testing (QST) in the form of tests of vibration perception thresholds (VPT) together with pegboard (pegboard is used to test manual dexterity) as important quantitative diagnostic tools. Exposure to vibration have shown an exposure-response effect on VPTs on a group level,[11–14] but on an individual level only indications of an exposure-response have been found. A study from our research group in 2020 was indicative of a clear exposure-response on an individual level.[15] There, associations between cumulative hand-arm vibration (HAV) exposure and elevated VPT was found not only among high exposed workers, but also among workers with exposures below the common exposure action value of 2.5 m/s^2 A8 (daily exposure averaged over 8 hours). However, one has to be careful to infer causal relationships due to the cross-sectional design of the above-mentioned study. These types of studies are also prone to exposure misclassification because they rely on workers to recall past exposure during previous years. An improved exposure assessment with individually adjusted exposure times is likely to increase the possibility to identify exposure-response relationships.

If a clear relationship between exposure and QST can be established on an individual level, this would be of great importance for the development of a risk model focusing on the neurological component. This would enable more accurate predictions about risks related to HAV exposure.

The present study is a 4-year cohort study using follow-up health examinations of road maintenance workers, including new participants to the group defined in a published cross-sectional study.[15] Our objective was to determine to what degree the indications of an exposure-response on an individual level between VPT and HAV would be reproduced in a study with a cohort design.

METHODS

Study design and setting

We used a prospective cohort design with one baseline and 0–2 follow-up health examinations after 2 and 4 years. Participants having only one health examination due to dropout, or inclusion in the last round of health examinations were also included in the study. Health examinations included blood samples (first round), pegboard and VPT tests. In 2013 we invited workers employed in a Norwegian road maintenance company to participate in the study. Workers assumed to have high exposure to HAV, and workers assumed to have low or no exposure to HAV were asked to participate. We assessed cumulative lifetime HAV exposure and measured the workers present HAV exposure in their natural work environment carrying out ordinary work tasks. Most of the workers participating in the study belonged to either the highway guardrail mounting department, or the rock face stabilising department. The guardrail workers mount or repair guardrails and get most of their HAV exposure from impact wrenches. The rock face stabilisers prevent roads and infrastructure from being hit by landslides or falling rocks. They get most of their HAV exposure from hand steered pneumatic rock drills. The health examinations were performed as a voluntary expansion of the ordinary health screening programme in the company which was offered during winter season. In addition to workers included in 2013, newly employed workers in the two departments were invited to participate in the study during the follow-up period.

Inclusion of participants

We invited 153 workers to participate in the study. One hundred and thirteen in the first round (2013/2014) and additionally 40 were invited in the second and third round (2015/2016 and 2018). Among the workers, everyone in the highway guardrail department and the rockface stabilising department assumed to have the highest HAV exposure in the company, were invited to participate (n=51 and n=50). To achieve a contrast to these higher exposed workers, we also invited workers from other departments assumed to have low or no exposure to HAV (n=52).

Exposure assessment

The main sources of HAV exposure among the participants were rock drills and impact wrenches. Contribution from other power tools were considered minuscule. Therefore, we based our exposure assessment on exposure to rock drills and impact wrenches. Based on workplace measurements we estimated HAV exposure from rock drills to an average vibration magnitude of 17 ms^{-2} and from impact wrenches an average magnitude of 7 ms^{-2}. These numbers correspond well to typical levels measured for these tools.[16] The measurements were done in accordance with relevant parts of ISO 5349 part 1 and 2.[17] The vibration metres Larson Davis HVM100 (Larson Davis, Depew, New York, USA) and Svantek 106 (Svantek, Warszawa, Poland) were used for the measurements. Based on time measurements in the field and interviews with workers, the average exposure time for rock drill use was 47 min/workday and for impact wrench use 15 min/workday. These exposure times and vibration magnitudes are equivalent to average daily exposure levels of 5.4 ms^{-2} A8 for rock drilling and 1.2 ms^{-2} A8 for impact wrench use. To help estimate lifetime cumulative HAV exposure, and changes in exposure levels during follow-up, questionnaires based on the VIBRISKS protocol[18] was used. The questionnaires included questions about daily exposure time, exposure days per week, weeks per year and years of exposure, in addition to questions about the use of any vibration tool other than the two main tools in the present and earlier occupational settings, as well as during leisure time. We also had access to company work records, which enabled us to refine the exposure assessment for the follow-up period on an individual level.

VPT

The participants underwent a QST of VPT based on the technical method described in ISO 13 091–1[19] using VibroSense Meter (VibroSense Dynamics, Malmø, Sweden). This instrument uses the von Bèkèsy method (the method of limits) with a gradually increasing and decreasing sinusoidal vibration of a probe with a flat circular surface of 3 mm diameter.[20] During the test, the hand was resting with the palm facing downwards. The finger to be tested rested with the pulp on the probe and a force indicator gave a light signal if the finger pressure was too high or too low to aid the test subject in maintaining correct pressure. The vibration magnitude of the probe increases in order of 3 dB/s, and the subjects presses down a button with the opposite hand when they sense the vibrations and release the button when they no longer sense the vibrations. This cycle is repeated four times and the vibration threshold for every frequency is calculated as the mean of the last three upper and lower limits of sensation. The second and fifth fingers on both hands were tested at seven frequencies: 8, 16, 32, 64, 125, 250 and 500 Hz. Thus, VPT was tested at a total of 28 (4×7) frequencies. The performance of the VPT test has been published in two studies applying similar test equipment and methods.[21 22] The participants had at least a 3-hour exposure-free period before the test and were asked not to use tobacco in any form the last hour before the test.

Manual dexterity (Grooved Pegboard Test)

Manual dexterity is the ability to make coordinated hand and finger movements to grasp and manipulate objects. It requires muscular and neurological functions to do these movements. We tested the participants manual dexterity by using Grooved Pegboard, which is a validated method.[23] It is a 12×12 cm metal board with 25 holes, placed 5×5. Above the metal plate there is a round concave deepening which serves as a reservoir for the small metal pegs. The pegs are 2.5 cm long and 2 mm thin. The pegs have a ridge along the length of the peg and each hole in the board has a small groove so that the pegs have to be turned to the right position as a key, to fit in the hole. The subject is instructed to pick up the pegs one by one and place them in the holes as fast as possible. The test performance is timed, and the fastest time achieved from two attempts was used as test score.

Blood samples

In the first round of health examinations, blood samples from the participants were analysed for parameters potentially relevant to the pathophysiology of reduced sensory nerve function. The information from results of blood sample testing were used as potential confounders in the analysis of the cross-sectional study of road workers,[15] but they did not confound associations between exposure and outcome. Thus, blood tests were not obtained in health examinations in the second or third round.

The procedures for the blood sampling have been described earlier.[15] The method used for analysis of cotinine, caffeine and nicotine has also been previously described.[24]

Statistical analysis

We used Stata V.16 (StataCorp, College Station, Texas, USA) for the statistical analysis. For the analysis of the characteristics of the study population we sorted the population based on work, reflecting main tool exposure (rock drill, impact wrench or no/low exposure). We used descriptive statistics with population means including SD. In analysis of the study population in the cross-sectional analysis in round one, cotinine, vitamin B_{12}, free T4, haemoglobin A1c (HbA1c) and carbohydrate-deficient transferring (CDT) was included in regression models for all frequencies for dominant second finger. Neither did confound the associations between exposure and outcome, thus we decided not to obtain further blood tests in round two and three.

To analyse exposure-response relationships between VPT and vibration exposure on an individual level, we used linear mixed models with subject ID as random intercept for VPT at 8 Hz, 16 Hz, 32 Hz, 64 Hz, 125 Hz, 250 Hz and 500 Hz for the dominant and non-dominant second and fifth fingers. Lifetime cumulative as well as last 12 months of exposure was calculated as mean vibration magnitude from tool (m/s^2) multiplied by exposure time in hours (h). We $\log_{10}$-transformed the exposure measures to correct for skewness. To enable log transformation, zero exposure to any of the two tools was substituted with $hour \times ms^{-2} = 1$. Exposure to rock drills and impact wrenches were included using separate terms in the same model. We

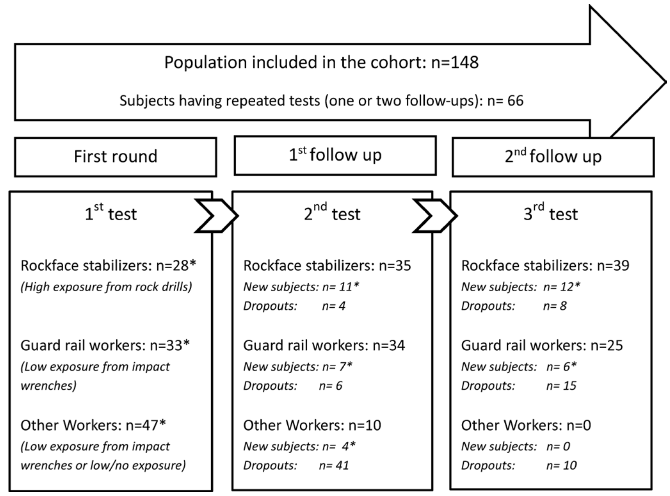

Figure 1 Participation data at baseline and at follow-up tests in the cohort . *Baseline individual test.

performed separate analyses using either lifetime or the last 12 months of exposure to check for possible changes in associations based on more recent exposure, thus not taking lifetime cumulative exposure into account.

The models were adjusted for age in 10-year intervals (20–29, 30–39, 40–49, 50–59 and 60–69). Models were also built using both age and age squared for adjustment. Outliers, defined as data points with standardised residuals exceeding three SD from the mean were excluded from the final models on a finger and frequency-wise basis to avoid the possibility of outliers interfering with the results. We set the significance level at $p \leq 0.05$.

All mixed model analyses were executed both including and excluding participants who had only one test (no follow-up tests). Including all participants, models showed a similar, but slightly greater measure of association between exposure and VPT. All participants were thus included in the final models. Testing the confounding effects of body mass index and height changed the estimate of the association with less than 2%. These variables were thus not included in final models. For the analysis of associations between vibration exposure and pegboard performance, we used the same exposure variables as described above, adjusting for age in 10-year intervals.

RESULTS

Group characteristics

A total of 148 male workers agreed to participate in the study (figure 1). Of those workers, 51 were exposed to high levels of mechanical vibrations from pneumatic rock drills used in rock face stabilising work and 46 workers were exposed to lower levels of vibrations from impact wrenches used in highway guardrail work. Three workers had high exposures to both tools. Among the 51 workers from other departments (general road inspection and maintenance work assumed to have little exposure) some had previous exposure (table 1). When investigating the exposure history of the participants in this group we recorded that many had exposures to impact wrenches, rock drills or similar mainly from previous work leaving only 21 workers unexposed to vibrating tools. Four workers did not show up for the scheduled health examination and one worker was excluded from the study because of known diabetes type I. There was a large dropout (n=41) between baseline and first follow-up among the no/low exposed workers because of reorganisation in the company. Some dropouts in the exposed groups were caused by

Table 1 Characteristics of the study population

	Work (type of exposure)*		
	Rock face stabilisers	Guardrail workers	Other low exposure jobs
	(Rock drill exp.)	(Impact wrench exp.)	(Low/no exposure)
n	51	46	51
Age, years, mean (SD)	35.6 (10.7)	43.5 (10.6)	39 (15.2)
Body mass index, kg m^{-2}, mean (SD)	25.8 (2.8)	28.9 (4.4)	27.4 (3.6)
Smoking or tobacco snuffing, n (%)†	28 (55)	28 (61)	26 (51)
Vibration exposure level, ms^{-2}‡	17	7	0–7
Vibration exposure, min/day‡	47	15	0–47
Vibration exposure, hours ms^{-2}, mean (SD)§	14 140 (19 713)	2982 (3514)	1218 (1753)
Vibration exposure, years, mean (SD)	8.3 (10.2)	11.8 (11.3)	11.9 (13.3)
Increased exposure during follow-up, n (%)¶	2 (8)	1 (5)	0
Decreased exposure during follow-up, n (%)¶	9 (45)	2 (10)	0
Finger/hand injuries, n (%)**	6 (11)	4 (21)	6 (11)
Hand function, n (%)††	4 (8)	11 (24)	3 (6)
White fingers, n (%)††	14 (27)	5 (11)	1 (2)
Finger numbness, n (%)††	23 (45)	15 (35)	4 (8)
Finger tingling, n (%)††	27 (53)	14 (30)	8 (16)

*n=3 subjects in the impact wrench group had in previous work also been exposed to rock drills. One subject in the impact wrench group was unexposed the last 6 years.
†n=3 subjects quit using tobacco during the follow-up period.
‡Estimates of average exposure level and exposure time are based on repeated measurements of typical work processes. Twenty-five workers in the low/no exposure jobs had exposure from impact wrenches, rock drills, mainly from previous work.
§Average cumulative baseline exposure based on measured average exposure from main tool multiplied by lifetime hours of exposure.
¶Subjects were asked about whether they had experienced any notable change in vibration exposure at work during the 4-year follow-up period.
**Finger/hand injuries were injuries which made it impossible to measure vibration perception thresholds (such as missing fingers).
††Subjects were asked about symptoms as well as hand functioning in activities of daily life.

difficulties in aligning the times for testing with the work rotation schedules.

VPT

We found a statistically significant exposure-response relationship between increasing cumulative vibration exposure from rock drills and VPT for several of the tested frequencies and fingers (table 2). A sensitivity analysis showed that the association was clear regardless of whether the analysis included all participants (n=148) or only the participants having repeated tests (n=66). Introducing age and age squared into the models did not change the coefficients of associations in the models. The second finger of the non-dominant hand was the most affected with a significant association at six out of seven test frequencies 8, 16, 32, 64, 125 and 500 Hz. At the other tested fingers there were significant associations at least at three frequencies (table 2). We also found a statistically significant association when limiting exposure to the last 12 months, and the associations were stronger at the higher frequencies with significant associations at 500 Hz for all four tested fingers (table 3).

We found a clear tendency of associations between exposure to impact wrenches and VPT (online supplemental tables 6 and 7). However, the results were not statistically significant.

Pegboard

We found no significant associations between pegboard score and exposure to impact wrenches (online supplemental tables 10–13). There was an association between pegboard score and

Table 2 Results summary from mixed models at dominant and non-dominant second and fifth fingers at seven test frequencies: associations between lifetime cumulative HAV exposure from rock drills and VPT; coefficients represent increase of VPT (dB) per 10-fold increase in lifetime cumulative exposure (hour×ms^{-2})†‡

Frequency	Dominant second finger (n=147, number of obs=248)§¶	Dominant fifth finger (n=146, number of obs=244)§¶	Non-dominant second finger (n=144, number of obs=242)§¶	Non-dominant fifth finger (n=147, number of obs=246)§¶
Hz	Coefficients (95% CI)**	Coefficients (95% CI)**	Coefficients (95% CI)**	Coefficients (95% CI)**
8	0.69 (0.07 to 1.31)*	0.85 (0.20 to 1.50)*	0.82 (0.25 to 1.40)*	0.66 (0.03 to 1.28)*
16	0.93 (0.34 to 1.52)*	0.94 (0.31 to 1.56)*	0.90 (0.24 to 1.56)*	0.79 (0.18 to 1.40)*
32	0.48 (–0.09 to 1.05)	1.00 (0.36 to 1.64)*	0.74 (0.11 to 1.37)*	0.65 (–0.00 to 1.31)
64	0.43 (–0.30 to 1.15)	0.91 (0.18 to 1.64)*	0.80 (0.00 to 1.59)*	0.63 (–0.15 to 1.42)
125	0.82 (0.01 to 1.62)*	0.88 (–0.04 to 1.80)	0.94 (0.08 to 1.81)*	0.92 (–0.09 to 1.92)
250	0.71 (–0.20 to 1.62)	0.75 (–0.37 to 1.88)	0.77 (–0.25 to 1.79)	1.10 (–0.04 to 2.24)
500	0.81 (–0.20 to 1.81)	1.11 (–0.13 to 2.36)	1.54 (0.36 to 2.72)*	1.50 (0.28 to 2.71)*

*$P\leq0.05$.
†Log_{10}-transformed exposure was used in models adjusted for age in 10-year intervals.
‡HAV exposure was calculated as lifetime cumulative exposure at each VPT test. Subject ID was used as random intercept in linear mixed models.
§Each subject was tested for VPT 1–3 three times (mean 1.7 times) with approximately 2 years between each test.
¶The number of participants was less than the total of n=148 for each tested finger because of participants having injured or missing fingertips.
**Rock drill exposure was adjusted for impact wrench exposure in the models.
HAV, hand-arm vibration ; VPT, vibration perception thresholds .

Table 3 Results summary from mixed models at dominant and non-dominant second and fifth fingers at seven test frequencies: associations between HAV exposure from rock drills and VPT; coefficients represent increase of VPT (dB) per 10-fold increase in last 12 months of exposure before tests (hour×ms^{-2}) †‡

Frequency	Dominant second finger (n=147, number of obs=248)§¶	Dominant fifth finger (n=146, number of obs=244)§¶	Non-dominant second finger (n=144, number of obs=242)§¶	Non-dominant fifth finger (n=147, number of obs=246)§¶
Hz	Coefficients (95% CI)**	Coefficients (95% CI)**	Coefficients (95% CI)**	Coefficients (95% CI)**
8	0.37 (–0.23 to 0.98)	0.46 (–0.18 to 1.11)	0.46 (–0.09 to 1.01)	0.11 (–0.50 to 0.73)
16	0.54 (–0.05 to 1.12)	0.56 (–0.05 to 1.18)	0.47 (–0.17 to 1.11)	0.37 (–0.22 to 0.97)
32	0.50 (–0.06 to 1.06)	0.79 (0.16 to 1.42)*	0.51 (–0.10 to 1.13)	0.47 (–0.15 to 1.10)
64	0.26 (–0.46 to 0.98)	0.37 (–0.34 to 1.08)	0.34 (–0.43 to 1.11)	0.79 (0.04 to 1.54)*
125	0.63 (–0.16 to 1.43)	0.54 (–0.34 to 1.43)	0.34 (–0.49 to 1.17)	1.06 (0.11 to 2.02)*
250	0.51 (–0.38 to 1.40)	0.99 (–0.07 to 2.10)	0.48 (–0.49 to 1.45)	1.21 (0.15 to 2.28)*
500	1.14 (0.15 to 2.14)*	1.51 (0.30 to 2.72)*	1.62 (0.46 to 2.79)*	1.53 (0.35 to 2.72)*

*P≤0.05.
†Log$_{10}$-transformed exposure was used in models adjusted for age in 10-year intervals.
‡HAV exposure was calculated as lifetime cumulative exposure at each VPT test. Subject ID was used as random intercept in linear mixed models.
§Each subject was tested for VPT 1–3 three times (mean 1.7 times) with approximately 2 years between each test.
¶The number of participants is less than the total of n=148 for each tested finger because of participants having injured or missing fingertips.
**Rock drill exposure was adjusted for impact wrench exposure in the models.
HAV, hand-arm vibration; VPT, vibration perception thresholds .

exposure to rock drills, with significant findings between lifetime cumulative exposure and pegboard score using dominant hand (table 4), and between last year of exposure and non-dominant hand (online supplemental table 8). These associations showed a paradoxical improvement of about 0.7 s (less than 2%) in the test score per 10-fold increase in exposure. There was a strong and significant age effect showing a worsening score for the age groups above 39 years.

DISCUSSION

In this 4-year cohort study, we found a significant exposure-response relationship between cumulative HAV-exposure from rock drills and VPTs on both second and fifth fingers at 16 of 28 test frequencies. Using only last 12 months of exposure showed a similar result, with significant exposure-response relationship at 8 of 28 test frequencies. We did not identify significant associations between exposure from impact wrenches and VPT. A small but significant relationship between exposure and pegboard score was found, showing paradoxically improved function with increasing cumulative exposure.

In order to discuss the clinical relevance of our findings, we will break down three of the results into more detail. For each added exposure unit of lifetime cumulative exposure (log hours×ms^{-2}) to rock drills, the VPT in the non-dominant fifth finger was increased by 1.5 dB and 0.92 dB at the 125 Hz and 500 Hz test frequency, respectively. The range of lifetime exposure was about 1–100 000 hours×ms^{-2} which equals 0–5 in the log-transformed variable. This means that a rise (worsening) in VPT in the range of 0–7.5 dB at 500 Hz and 0–4.6 dB at 125 Hz, could be explained by the exposure. Using last 12 months of exposure, the perception threshold was increased by 1.53 dB in the non-dominant fifth finger at the 500 Hz test frequency. The range of exposure was 1–2884 hours×ms^{-2} which equals 0–3.46 in the log-transformed variable. This means that a rise in VPT in the range of 0–5.2 dB could be explained by the exposure last 12 months. As an example, a rise in VPT of 6 dB from 114 dB to 120 dB in a finger is equivalent to a rise from 0.5 ms^{-2} in VPT to 1 ms^{-2} in VPT. We argue that this range is clinically relevant, because at 125 Hz a VPT of 0.7 ms^{-2} would be classified as a ‘possible disorder’ and 1 ms^{-2} as a ‘probable disorder’ according to UK diagnostic criteria.[25]

The small significant improvement in pegboard performance associated with exposure should be interpreted with care because it is unlikely from a clinical standpoint that increased exposure to HAV leads to better performance in Grooved Pegboard Tests. Pegboard testing is considered a useful tool for the diagnosis of HAVS and carpal tunnel syndrome as a way to quantify functional impairment of the hand.[10 26] A more expected outcome would be that the exposure, which cause a deterioration in VPT, also affects manual dexterity of the fingers and hands negatively. It is reasonable to assume that the association was caused by a healthy worker selection bias effect. Workers who are starting to feel that their manual dexterity and ability to handle objects are deteriorating are probably more likely to change jobs, leaving the remaining individuals as healthy ‘survivors’ who are more resilient against HAV exposure than those who left this work. The healthy worker effect could also reduce the association between HAV exposure and VPT. However, probably not as much, because increased (worsened) VPT is a sign which the workers may not be conscious about and may precede symptoms such as numbness, white fingers and reduced manual dexterity. Thus, it is possible that an association between HAV exposure and reduced pegboard score would be found at a later stage. Another possible source of bias could be a learning effect between the

Table 4 Mixed models: associations between lifetime cumulative hand-arm vibration exposure from rock drills and pegboard score using dominant hand; coefficients represent increase of performance time in the pegboard test (seconds) per 10-fold increase in lifetime cumulative exposure (hour×ms^{-2})

Age (years)	Coefficient	95% CI
20–29	1 REF	
30–39	–0.13	–3.29 to 3.03
40–49	4.83	1.74 to 7.91*
50–59	9.71	6.21 to 13.21*
60–69	15.53	10.93 to 20.13*
Rock drill exposure		
Lifetime cumulative	–0.70	–1.29 to –0.11*
Constant	57.36	54.99 to 59.73*

*Significant at p≤0.05.

pegboard tests in the 4-year follow-up period. Results from the Grooved Pegboard Tests showed a very strong age-effect and the results were in general similar to the normal values found in the study by Ruff and Parker.[23] The results from our sensitivity analyses for the VPT tests showed that VPT does not have a complete linear relationship with age in a normal population. These findings are in accordance with some of the findings in a recent publication where the age group 50–59 showed a tendency of better performance in the VPT tests compared with the 40–49 year age group at 250 Hz and 500 Hz for the second finger and at 125 Hz, 250 Hz and 500 Hz for the fifth finger.[27]

A strength in our study was that we used a 4-year follow-up with exposure assessments where we assessed exposure times with adjustments on an individual level. A limitation was the relatively large dropout among the low/no exposed workers prior to the first follow-up, where several workers left the company as a result of a major reorganisation. This may have diluted the associations as the remaining group in general had a higher cumulative exposure compared with the dropouts. There is also a general limitation regarding the uncertainty associated with estimation of lifetime cumulative exposure to HAVs. Recall bias is a well-known problem[28 29]; it is not possible to get accurate knowledge about variables such as exposure time, tool maintenance and individual work technique in retrospect. However, we were able to do additional analyses restricted to the last 12 months of exposure, a period where we had good knowledge about the exposure time based on access to information about tool use from company records. Concurrent measurements of exposure magnitude provided a good estimate of HAV exposure magnitude from the tools being used in this limited time period. However, variations based on individual working techniques, operating conditions and tool maintenance adds to uncertainty related to the exposure estimates. These analyses confirmed the analyses using lifetime cumulative exposure. This may also indicate that VPTs among the workers were affected by changes in exposure intensity during the last 12-month periods during the follow-up.

In a cross-sectional study[15] we analysed data from the same study population. The exposure-response relationship between rock drill exposure and VPTs on an individual level indicated by that study has been confirmed in our present cohort study. Indications of an exposure-response between exposure to impact wrenches and VPTs was however not confirmed in our cohort study. We found a tendency of an association, however not statistically significant. This could be caused by the dropout of low-exposed workers which may have reduced the efficiency of the study due to less exposure contrast.

Studies have indicated that 31.5 Hz and 125 Hz should be the preferred test frequencies,[10 30] which are in accordance with the recommendations given in the ISO standard ISO 13 091–1.[19] Our findings suggest that testing VPTs at 500 Hz also should be included. The strong and significant association found between rock drill exposure and VPT at the 500 Hz test frequency for all four tested fingers in the present follow-up study corroborates the findings in our earlier cross-sectional analysis,[15] and indicates that the 500 Hz test frequency may be the most sensitive for investigating VPTs as an early indication of HAVS resulting from exposure to the tools included in the present study.

Earlier cross-sectional studies have indicated an exposure-response relationship between HAV exposure and VPT.[12 13 15] To our knowledge, our study is the first cohort study which shows a clear exposure-response relationship, also on an individual level. Our study adds new knowledge on this relationship and can contribute to the generation of new models for risk assessments which focus on the neurological component of HAVS, using VPT testing as an objective measure of early signs of disease.

Acknowledgements We appreciate the participation of the workers and the company who made it possible to conduct the study.

Contributors TC: guarantor, project design, data collection, data interpretation, draft writing, revising and approval of final document. L-KL: project design, data interpretation, revising and approval of final document. BU: project design, data collection, data interpretation, revising and approval of final document. KF: project design, data collection, data interpretation, revising and approval of final document. K-CN: project design, data collection, data interpretation, revising and approval of final document, and supervising.

Funding The RVO-fond (Regional Safety Representatives fund) helped finance the study.

Disclaimer The RVO-fond did not play any role in the study design; in the collection, analysis and interpretation of data; in the writing of the report; or in the decision to submit the paper for publication.

Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and was approved by Ethical Research Committee of South-East Norway (approval number 2013/1031). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request. Data are stored as de-identified participant data.

ORCID iDs

Thomas Clemm http://orcid.org/0000-0002-2506-9659
Lars-Kristian Lunde http://orcid.org/0000-0001-6219-9244
Bente Ulvestad http://orcid.org/0000-0001-7674-3001

REFERENCES

1 Taylor W. The hand-arm vibration syndrome--diagnosis, assessment and objective tests: a review. *J R Soc Med* 1993;86:101–3.
2 M, P, IS M. *Pasientutredninger ved de arbeidsmedisinske avdelinger I 2019, STAMI*. Norway: The National Institute of Occupational Health in Norway, 2021.
3 Forsakring A. *Vibrationsskador -En skakig historia*. Sweden: AFA Forsakring, 2018.
4 Griffin MJ. Measurement, evaluation, and assessment of peripheral neurological disorders caused by hand-transmitted vibration. *Int Arch Occup Environ Health* 2008;81:559–73.
5 Chetter IC, Kent PJ, Kester RC. The hand arm vibration syndrome: a review. *Cardiovasc Surg* 1998;6:1–9.
6 Futatsuka M, Ueno T, Sakurai T. Cohort study of vibration-induced white finger among Japanese forest workers over 30 years. *Int Arch Occup Environ Health* 1989;61:503–6.
7 Koskimies K, Pyykkö I, Starck J, *et al*. Vibration syndrome among Finnish forest workers between 1972 and 1990. *Int Arch Occup Environ Health* 1992;64:251–6.
8 Nilsson T, Wahlström J, Burström L. Hand-Arm vibration and the risk of vascular and neurological diseases-A systematic review and meta-analysis. *PLoS One* 2017;12:e0180795.
9 International_Organization_for_Standardization. *ISO 5349-1:2001 Mechanical vibration - Measurement and evaluation of human exposure to and-transmitted vibration - Part 1: General requirements*. United Kingdom: ISO, 2001.
10 Poole CJM, Bovenzi M, Nilsson T, *et al*. International consensus criteria for diagnosing and staging hand-arm vibration syndrome. *Int Arch Occup Environ Health* 2019;92:117–27.

11 Lundström R, Nilsson T, Burström L, *et al*. Vibrotactile perception sensitivity and its relation to hand-arm vibration exposure. *Cent Eur J Public Health* 1995;3 Suppl:62–5.
12 Lundström R, Nilsson T, Burström L, *et al*. Exposure-Response relationship between hand-arm vibration and vibrotactile perception sensitivity. *Am J Ind Med* 1999;35:456–64.
13 Virokannas H. Dose-Response relation between exposure to two types of hand-arm vibration and sensorineural perception of vibration. *Occup Environ Med* 1995;52:332–6.
14 Sauni R, Pääkkönen R, Virtema P, *et al*. Dose-Response relationship between exposure to hand-arm vibration and health effects among metalworkers. *Ann Occup Hyg* 2009;53:55–62.
15 Clemm T, Færden K, Ulvestad B, *et al*. Dose-Response relationship between hand-arm vibration exposure and vibrotactile thresholds among roadworkers. *Occup Environ Med* 2020;77:188–93.
16 Griffin M, Pitts PM, Kaulbars U. Guide to good practice on hand-arm Vibration., in VIBRISKS. 2006, European Commission, quality of life and management of living resources programme key action 4. *Environment and Health*:35–6.
17 International_Organization_for_Standardization. ISO 5349-1 & 2:2001 Mechanical vibration - Measurement and evaluation of human exposure to and-transmitted vibration - Part 1: General requirements - Part 2. In: *Practical guidance for measurement at the workplace*. ISO, 2001.
18 Griffin MJ, Bovenzi M. *VIBRISKS final technical report, protocol for epidemicological studies of hand-transmitted vibration, Annex 1, appendix 8a*. University of Southampton UK, University of Trieste Italy, 2007.
19 International_Organization_for_Standardization. ISO 13091-1 Mechanical vibration - Vibrotactile perception thresholds for the assessment of nerve dysfunction - Part 1. In: *Methods of measurement at the fingertips*. ISO, 2001.
20 Lundborg G, Lie-Stenström AK, Sollerman C, *et al*. Digital vibrogram: a new diagnostic tool for sensory testing in compression neuropathy. *J Hand Surg Am* 1986;11:693–9.
21 Gerhardsson L, Gillström L, Hagberg M. Test-Retest reliability of neurophysiological tests of hand-arm vibration syndrome in vibration exposed workers and unexposed referents. *J Occup Med Toxicol* 2014;9:38.
22 Ekman L, Persson Löfgren J, Dahlin LB. Examining practice effects in repeated measurements of vibration perception thresholds on finger pulps of healthy individuals - Is it possible to improve your results over a clinically relevant test interval? *PLoS One* 2019;14:e0226371.
23 Ruff RM, Parker SB. Gender- and age-specific changes in motor speed and eye-hand coordination in adults: normative values for the finger tapping and grooved Pegboard tests. *Percept Mot Skills* 1993;76:1219–30.
24 Bast-Pettersen R, Ulvestad B, Færden K, *et al*. Tremor and hand-arm vibration syndrome (HAVS) in road maintenance workers. *Int Arch Occup Environ Health* 2017;90:93–106.
25 Seah SA, Griffin MJ. Normal values for thermotactile and vibrotactile thresholds in males and females. *Int Arch Occup Environ Health* 2008;81:535–43.
26 Amirjani N, Ashworth NL, Olson JL, *et al*. Validity and reliability of the Purdue Pegboard test in carpal tunnel syndrome. *Muscle Nerve* 2011;43:171–7.
27 Ekman L, Lindholm E, Brogren E, *et al*. Normative values of the vibration perception thresholds at finger pulps and metatarsal heads in healthy adults. *PLoS One* 2021;16:e0249461.
28 Gerhardsson L, Balogh I, Hambert P-A, *et al*. Vascular and nerve damage in workers exposed to vibrating tools. The importance of objective measurements of exposure time. *Appl Ergon* 2005;36:55–60.
29 Palmer KT, Haward B, Griffin MJ, *et al*. Validity of self reported occupational exposures to hand transmitted and whole body vibration. *Occup Environ Med* 2000;57:237–41.
30 Rolke R, Rolke S, Vogt T, *et al*. Hand-Arm vibration syndrome: clinical characteristics, conventional electrophysiology and quantitative sensory testing. *Clin Neurophysiol* 2013;124:1680–8.