Bad vibrations: Exposure-response between rock drilling and vibration sensitivity at the fingertips

A Doctoral Thesis by

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Content

COMMON ABBREVIATIONS:

CTS: Carpal tunnel syndrome
EAV: Exposure action value
ELV: Exposure limit value
HAV: Hand-arm vibration
HAVS: Hand-arm vibration syndrome
m/s^2: Meter per second squared (unit for acceleration)
m/s^2A8: Meter per second squared averaged over an eight-hour work shift (daily vibration)
VPT: Vibration perception threshold

1. SCIENTIFIC ENVIRONMENT

This PhD is affiliated with Institute of Health and Society at the Faculty of Medicine, University of Oslo, where all mandatory lectures have taken place. The PhD-project was initiated and granted by the National Institute of Occupational Health in Norway. My other employer Mesta AS, has supported this PhD project by giving me permission to collect data and time to work on the project. Data collection, both exposure measurements and health examinations has been done at several Mesta locations in Norway.

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Last, but not least I want to thank my whole family, and especially the three most important people in my life; My wife Hege and my two sons Tobias and Herman. Thank you for your patience, support and for always being there for me.

3. ABSTRACT

3.1 Abstract (English)

Background

Workers exposed to Hand arm vibration (HAV) from handheld or hand guided power-tools are at risk for injuring the small nerves and blood vessels of the finger and hands, causing vascular and neurological dysfunction which may lead to functional impairments and the occupational disease Hand-arm Vibration syndrome (HAVS). HAVS is traditionally determined by the onset of vascular symptoms (white fingers) and most of the studies on exposure-response relationships have focused on the vascular symptoms. However, neurological signs such as reduced tactile sensibility and vibration perception usually precedes the vascular symptoms. Nevertheless, current knowledge of dose-response mechanisms between HAV exposure and neurological symptoms is limited.

There are different approaches to exposure measurements which may introduce bias in the evaluation of potential hazards from vibration exposure. This is especially a challenge when assessing exposure from hand guided tools such as rock drills, where individual working techniques most likely will influence exposure.

To detect possible dose-response relationships it is important that exposure is measured correctly, and response mechanisms should be quantified, preferably in a study with a cohort design.

Aims

To assess exposure-response relationships between HAV exposure and vibration perception thresholds (VPT) on an individual level.

To assess exposure-response relationships between HAV exposure and pegboard score on an individual level.

Asses possible bias in exposure measurements introduced by choice of measurement approach, specifically placement of vibration sensors (accelerometers).

Methods

We followed up 148 workers from different departments in a road maintenance company, exposed to different levels of HAV exposure. We assessed lifetime cumulative exposure expressed as m/s^2 multiplied by hours of exposure as well as average daily vibration exposure (m/s^2 A8) based on vibration measurements and questionnaires. Health examinations including VPT tests (a measure of vibration perception at the fingertips) and Pegboard tests (a measure of hand dexterity) were carried out at baseline, 2 years and 4 years. We did VPT tests on 2nd and 5th fingers on both hands and included seven test frequencies from 8 – 500 Hz. We investigated associations using linear regression models on cross sectional data from baseline tests, and linear mixed models on cohort data, setting the significance level at $p \leq 0.05$.

To assess possible bias caused by tool-attached or hand-attached accelerometers, simultaneous measurements on jack leg drills with the two attachments was done.

Results

At baseline, in the first round of health examinations the participants were either exposed to rock drills (n=33), impact wrenches (n=52) or none of these tools (n=19). Workers exposed to rock drills had an average daily exposure of 5.4 m/s^2 A8 which is higher than the exposure limit value (ELV) of EU countries, UK and US at 5 m/s^2 A8. Workers exposed to impact wrenches were exposed to an average daily exposure of 1.2 m/s^2 A8 which is below the exposure action value (EAV) at 2.5 m/s^2 A8 in the above-mentioned countries. An exposure – response was found between exposure to rock drills and VPT and number of days exposed to 5.4 m/s^2 A8. A stronger exposure-response was found when using the exposure measure m/s^2 (vibration magnitude of tool) times lifetime hours of exposure. Using this measure, a clear indication of an exposure-response was also found among the moderately exposed workers who used impact wrenches as their main tool. In the cohort, the total number of participants was 148. There was a significant exposure-response relationship between VPT and lifetime cumulative exposure (hours x m/s^2) found on an individual level in both studies. In the cohort-study a significant relationship was found for 16 of 28 test frequencies. The highest rise in VPT (worsening) was found at the 500 Hz test frequency with 1.54 dB increased VPT per tenfold increase in lifetime cumulative exposure. No deterioration in pegboard performance associated with HAV exposure was found among the participants.

Simultaneous measurements of tool-attached and hand-attached accelerometers showed a significant difference (9.5 m/s^2; $p \leq 0.05$). The hand attached accelerometer showed a lower vibration magnitude for all workers (range of difference: 2.3 - 14.6). It was observed that individual working techniques (in the way the workers held the tools) is an important variable which may influence the difference between the two measurement methods.

Conclusions:

Exposure from rockdrills was associated with a significant increase (worsening) in VPT with an exposure-response relationship also on an individual level. Risk models of HAVS may be based on exposure-response relationships between HAV exposure and VPT. Among workers exposed to relatively low exposure levels from impact wrenches below the exposure action value (EAV) of 2.5 m/s^2(A8), there was also a clear tendency of increased VPT, indicating the EAV is not a safe limit level. The 500 Hz test frequency should be studied, as a possible marker of early signs related to reduced tactile sensitivity.

Hand-attached accelerometers may cause a bias towards underestimating exposure. In most cases it is a reasonable assumption that the true exposure lies between the measurement results achieved with hand-attached and tool-attached accelerometers. The choice of attachment may infer bias that should be considered during performance of studies, and relevant for interpretation of study results. To avoid misclassification of HAV exposure careful assessments on individual working techniques and thorough considerations of measurement approach, including accelerometer placement is important.

3.2 Sammendrag (Norsk)

Bakgrunn

Arbeidstakere utsatt for hånd-arm vibrasjoner (HAV) fra håndholdte eller håndstyrte verktøy er i risiko for å skade de små nervene og blodkarene i fingrene, noe som kan forårsake vaskulær og nevrologisk dysfunksjon som kan føre til funksjonsnedsettelser og yrkessykdommen hånd-arm vibrasjons syndrom (HAVS). Arbeidstakere som får HAVS må i mange tilfeller omskoleres for å unngå ytterligere forverring. Det er de iøyenfallende vaskulære symptomene (hvite fingre) som tradisjonelt har fått mest oppmerksomhet og de fleste studier på dose - respons har fokusert på vaskulære symptomer. Imidlertid intreffer vanligvis nevrologiske symptomer som redusert taktil følsomhet og -vibrasjonsoppfattelse før de vaskulære symptomene, og det er nerveskadene som i størst grad forårsaker funksjonsnedsettelse. Likevel er dagens kunnskap om dose-respons mekanismer mellom HAV-eksponering og nevrologiske symptomer begrenset.

Valg av metode for eksponeringsmålinger kan introdusere skjevhet i evalueringen av potensielle farer ved vibrasjonseksponering. Dette er spesielt en utfordring når man vurderer eksponering fra håndstyrte verktøy som fjellbor, der individuelle arbeidsteknikker kan påvirke nivået på eksponeringen.

For å oppdage mulige dose-respons sammenhenger er det viktig at eksponeringen måles riktig, og responsmekanismer kvantifiseres, fortrinnsvis studier med kohortdesign.

Mål

Å kartlegge og eventuelt avdekke dose-respons sammenheng mellom HAV-eksponering og vibrasjons-persepsjonsterskler (VPT) på individnivå.

Å kartlegge og eventuelt avdekke dose-respons sammenheng mellom HAV-eksponering og pegboard score på individnivå.

Å vurdere mulig skjevhet i eksponeringsmålinger introdusert ved valg av målemetode, spesifikt plassering av vibrasjonssensorer (akselerometre).

Metoder

Vi fulgte opp 148 arbeidere fra ulike avdelinger i et veivedlikeholdsselskap, utsatt for ulike nivåer av HAV-eksponering. Vi vurderte kumulativ livstidseksponering uttrykt som m/s^2 multiplisert med eksponeringstimer samt gjennomsnittlig daglig vibrasjonsnivå (m/s^2 A8) basert på vibrasjonsmålinger og spørreskjema. Helseundersøkelser inkludert VPT-tester (test av føleterskler på fingertupp) og pegboard-tester (test av fingerferdighet) ble utført ved baseline, 2 år og 4 år. Vi utførte VPT-tester på pekefinger og lillefinger på begge hender og inkluderte syv testfrekvenser fra 8 – 500 Hz. Vi undersøkte assosiasjoner ved hjelp av lineære regresjonsmodeller på tverrsnittsdata fra baseline-testene, og lineære «mixed models» på kohortdata, og satte signifikansnivået til p≤0,05.

For å vurdere mulig skjevhet forårsaket av verktøyfestede eller håndfestede akselerometre, ble det gjort samtidige målinger på fjellbor med de to festepunktene. Det ble gjort totalt 29 simultane målinger på fem arbeidere under realistiske arbeidsforhold i et kvasi-eksperimentelt studiedesign.

Resultater

Ved baseline, i første runde med helseundersøkelser var det inkludert arbeidere som enten var eksponert for fjellbor (n=33), muttertrekkere (n=52) eller ingen av disse verktøyene (n=19). Arbeidere eksponert for fjellbor hadde en gjennomsnittlig daglig eksponering på 5,4 m/s^2 A8, som er høyere enn grenseverdien for eksponering (ELV) i EU, Storbritannia og USA på 5 m/s^2 A8. Arbeidstakere eksponert for muttertrekkere ble utsatt for en gjennomsnittlig daglig eksponering på 1,2 m/s^2 A8, som er under tiltaksverdien for eksponering (EAV) på 2,5 m/s^2 A8 i de ovennevnte landene. Det ble funnet dose - respons mellom eksponering for fjellbor og VPT og antall dager eksponert for 5,4 m/s^2 A8. En sterkere eksponeringsrespons ble funnet ved bruk av eksponeringsmålet m/s^2 (vibrasjonsstyrken til verktøyet) multiplisert med antall timer med eksponering. Med dette eksponeringsmålet ble det også funnet en klar indikasjon på dose-respons blant de moderat eksponerte arbeidstakere som hadde muttertrekker som hovedverktøy. I kohort-studien var det totale antallet deltakere 148. Det var en signifikant dose-respons sammenheng mellom kumulativ eksponering (timer multiplisert med m/s^2) og VPT på individnivå i begge studiene. I kohortstudien ble det funnet en signifikant sammenheng for 16 av 28 testfrekvenser. Den høyeste økningen i VPT (forverring) ble funnet på 500 Hz testfrekvens med 1,54 dB økt VPT per ti-dobling i kumulativ eksponering. Det ble ikke funnet noen forverring av pegboard score assosiert med HAV-eksponering blant deltakerne.

Samtidige målinger av verktøymonterte og håndfestede akselerometre viste signifikant forskjell (9,5 m/s^2; p≤0,05). Det håndfestede akselerometeret viste en lavere vibrasjonssyrke for alle arbeidere (range: 2,3 - 14,6 m/s^2). Det ble observert at individuelle arbeidsteknikker (knyttet til måten arbeiderne holdt verktøyene på) er en viktig faktor som kan påvirke forskjellen mellom de to målemetodene.

Konklusjon:

Eksponering fra fjellbor var assosiert med en signifikant økning (forverring) i VPT med dose-respons på individnivå. Dette kan gi grunnlag for risikomodeller for HAVS som bygger på dose-respons sammenhengen mellom HAV-eksponering og VPT. Blant arbeidere eksponert for relativt lave eksponeringsnivåer fra muttertrekkere under tiltaksverdi (EAV) på 2,5 m/s^2 A8, var det også en klar tendens til økt VPT, noe som indikerer at EAV ikke er et trygt vibrasjonsnivå. Testfrekvensen på 500 Hz bør vurderes som en mulig markør for tidlige tegn relatert til redusert taktil følsomhet, men mer forskning er nødvendig for å kunne stadfeste dette.

Håndfestede akselerometre kan forårsake systematisk skjevhet i måleresultater som fører til underestimering av eksponering. I de fleste tilfeller er det en rimelig antagelse at den sanne eksponeringen ligger mellom måleresultatene oppnådd med håndfestede og verktøyfestede akselerometre. Valg av akselerometerplassering kan føre til systematisk skjevhet som bør hensyntas ved utførelse av studier, og det er også relevant å vurdere ved tolkning av resultater. For å unngå feilklassifisering av HAV-eksponering er det viktig med nøye vurderinger av individuelle arbeidsteknikker og grundige vurderinger av målemetoden, inkludert plassering av akselerometeret, både i dose-responsstudier og i evaluering av eksponering i arbeidshelsesammenheng.

4. INTRODUCTION

4.1 History of HAVS

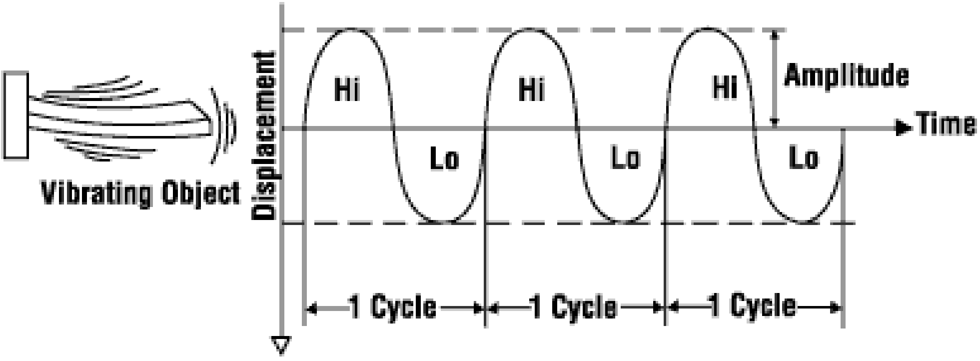
"..the trouble seems to be caused by the vibrations of the tool, and cold. If these features can be eliminated the trouble can be decidedly lessened". These are the words of Dr. Alice Hamilton in 1918 after she had led an investigation by US Bureau of Labor and found the symptoms pain, numbness, and white fingers among stone cutters in limestone quarries in Indiana. This was just a few years after Giovanni Loriga in 1911 linked Raynaud`s phenomenon to hand-arm vibration (HAV) exposure for the first time [1]. He had observed

the symptoms among users of handheld pneumatic rock drills in French mines. The condition has been referred to as Raynaud's Phenomenon of occupational origin, Secondary Raynaud`s Phenomenon, Traumatic Vasospastic Disease, Vibration White Finger (VWF), Spastic Anemia and Hand-Arm Vibration Syndrome (HAVS). Today, HAVS is the most used term. Hand steered pneumatic rock drills proved to be an incredibly effective tool when it was introduced in the mining industry around 1890. With a sledgehammer and chisel, one worker could under normal conditions manage to make a 20 cm hole in one hour, and two men working together -one of the workers holding the chisel rotating it 90 degrees between every hammer stroke- could make about 60 cm. Instead of 40 – 50 strokes a minute with a chisel and a sledgehammer, the new tool could manage more than 1000 strokes a minute. The design was refined over the years, and in the 1950`s the jackleg hammer was introduced: A handheld rockdrill was attached flexibly to a portable air cylinder. This design was extremely durable and effective, and one worker could drill a 60 cm hole in one minute [2]. However, the new tools were not harmless to humans. They were called "Widow makers" because of the widespread lung disease caused by the crystalline silica dust produced during drilling. In addition, there was another health risk, which was documented by Hamilton. She found a prevalence of HAVS related symptoms of 89 % among the quarry workers in Indiana [3]. In 1978, a new investigation by Taylor et al. in the same quarry in Indiana found a prevalence of 80 % among the workers [4]. In 1962 Williams et al. documented Raynaud's Phenomenon of occupational origin among uranium miners using jackleg hammers. This type of hand steered rock drill is still today widely in use and is commonly used in mining operations and construction work. The design of the drill is almost unchanged since the 50's. In 1999 more than 40 000 former coal miners in United Kingdom received 500 million British pounds in a compensation deal, because the coal companies had not informed the workers about the health risks of working with pneumatic jackleg hammers. One of the victims, Fred Smith told the newspaper The Guardian on the 23rd of January 1999: "I wear special braces on my hands now, but they are still painful, especially during the night, my hands swell up and the pain extends up to my elbows. I cannot snap my fingers and I have trouble opening doors and fastening buttons. I used to do my own car maintenance, mow the lawn, and look after the garden. But now I do nothing". Mr. Smith did not expect to be able to work again. The evidence of the risk of damage from vibrating tools is solid [5]. However, how ergonomic factors and vibration properties of tool-types may impact the risk of injury is largely unknown. What we do know is that a whole range of tools, from heavy pneumatic rockdrills to battery driven impact wrenches and small dentist tools may cause vibration related injuries to the fingers [1, 6]. Vibrating tools are used throughout the industrialized world today, and in many cases the vibration exposure are so high that workers are at risk for injuring their hands and fingers [7], and many are also at risk of falling permanently out of work [8]. In a large survey among Norwegian workers, 39% of metal workers reported substantial exposure to HAV daily. Among carpenters, mechanics and construction workers respectively 34%, 31% and 27% reported substantial exposures to HAV [9].

4.2 Mechanical properties of vibrations

Vibration can be defined as a mechanical phenomenon whereby oscillations occur about an equilibrium point [10]. Mechanical vibrations have four qualities which are mathematically linked. Frequency, velocity, magnitude, and acceleration. A small boat in large waves is a good illustration of those qualities: The amplitude is how far the boat moves in a vertical direction from the neutral position (sea level) to the top of the wave. The velocity is zero at the wave top and at the trough in the moment the oscillating movement changes direction. From the trough there is an acceleration to the point midway between the trough and the wave crest. At this point the velocity is at its maximum, while the acceleration is 0. Thus, the velocity and the acceleration of the movement is inversely proportional. The frequency is the number of completed cycles within one second. Figure 1 illustrates the relationship between magnitude, velocity, and acceleration. For the assessment of human exposure to vibrations, measurement equipment that measures the acceleration of the vibrations is used (section 4.6).

Figure 1: Mechanical properties of vibrations illustrated as a sinus curve with a frequency of 3 Hz



Source: Canadian Centre for Occupational health and Safety

To be able to understand and evaluate human exposure to vibrations it is useful to characterize vibrations by three properties: Frequency, amplitude, and direction. These properties of mechanical vibrations may affect the risk for adverse health effects for humans who are exposed to the vibrations.

4.2.1 Frequency

The simplest form of vibration is a simple periodic and sinusoidal vibration. A unidirectional movement about an equilibrium which is repeated and unchanged over time. These vibrations are deterministic. If one movement cycle is completed in one second, we say that the frequency of the vibration is one Hertz (Hz). If ten cycles are completed in one second, the frequency is ten Hz. A mechanical metronome used for music practice is an example of an equipment which exhibits a simple periodic sinusoidal vibration. However, the vibrations that are produced in power tools are more complex. Usually, they are of the random type (non-deterministic) and has a multi-frequency range.

Vibrations are energy that travels in wave forms. Thus, it needs a medium to travel through. When this medium is a machine or parts of a tool such as the hand grips, then the vibrations can be transmitted to the human body and travel through the finger, hands, and arms. All dynamic systems have a resonance frequency, and often many. If a dynamic system is exposed to its resonance frequency the system will vibrate at a higher amplitude. An example of such a dynamic system is a bridge, and there are cases of bridges that have collapsed due to high winds causing the bridge to oscillate at the resonance frequency. The finger-hand-arm system is also an example of a dynamic system which has resonance frequencies (see section 4.2.5).

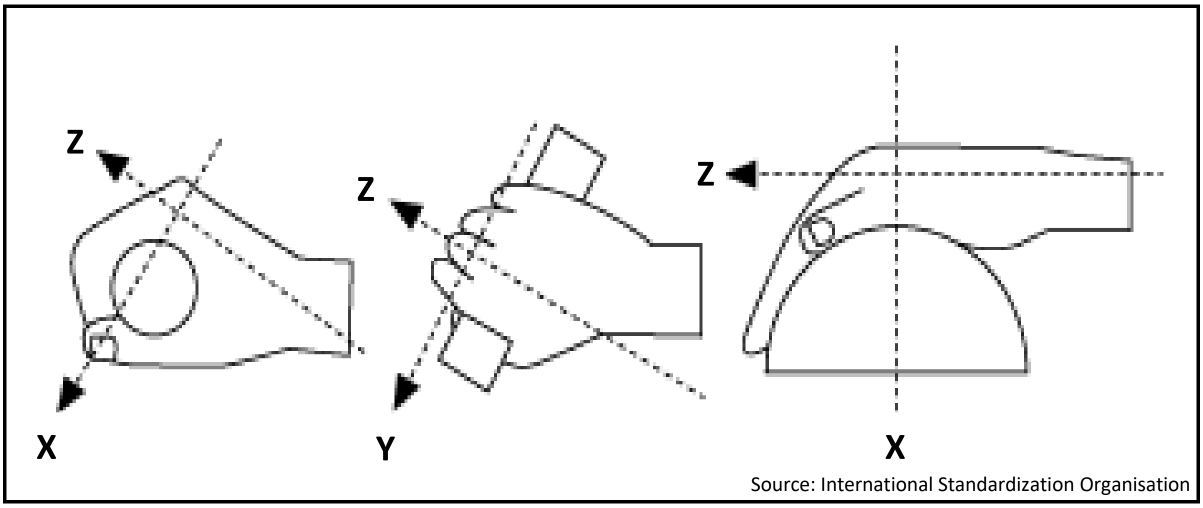
4.2.2 Amplitude

The amplitude is the distance a vibrating surface moves from its point of equilibrium to the peak distance of the movement at the position when the surface starts to move back towards equilibrium. If you have two different power tools which vibrates at the same frequency, but one of them at a higher amplitude, then this means that more energy is transmitted to the fingers from the tool with the highest amplitude vibrations, and it is plausible that the risk of injury to the biological tissues in the fingers increases. It is possible with two exposure doses containing the same amount of energy from tools with different vibration magnitudes if the tool with lower magnitudes is used for a longer period. A study by Bovenzi indicated that long exposure times (with low vibration magnitudes) seemed to be more harmful than shorter exposures (and higher vibration magnitudes) because the reduction in blood circulation of the fingers during exposure needed a longer recovery time for the longest exposures [11].

4.2.3 Direction

Vibrations from a power tool does not only oscillate in one direction. Even though there usually is a main direction for the vibrations there is always vibrations along other axes. For vibration measurements it is standard procedure to measure along three axes, X, Y and Z where X and Y are 90° to each other in the same plane and the Z-axis which is 90° transverse to the plane of the X and Y axes (figure 2).

Figure 2: The three measurement axes



Source: International Standardization Organisation

The angle that the vibrations have at the driving point (point of contact between the tool and finger/hand) affects how effectively the vibrations are transmitted to the hand, and how the vibrations are propagated through the different layers of human tissue in the fingers and hands (section 4.2.5).

4.2.4 Transients

A transient refers to a momentary variation, or an incident lasting a short time. Transient vibrations are vibrations containing impulses or shocks of large amplitudes. Examples of such transient in HAV exposure is when the cutting blade of a land mower hits a twig, or when the drill rod of a rock drill gets stuck in the rock. The impulsiveness of vibrations has been shown to be of importance when evaluating symptoms of HAVS. A study by Starck showed that the impulsiveness of HAV exposure from grinding wheels, chains saws and pneumatic hammers partly explained the symptoms of vibration induced white fingers [12]. However, the impulsiveness of vibrations is to a large degree left out when HAV exposure is measured as a time weighted root mean square average, according to the standardized method (se section 5.6).

4.2.5 The response of the finger-hand-arm as a dynamic system

When a human is exposed to mechanical vibrations, i.e., from the handle of a power tool, the way the vibration energy is transmitted and dissipated through the human tissues (skin, fatty tissues, muscles, bone) in the finger, hand and sometimes arm is complicated. As mentioned it depends on frequency, direction, and the amplitude of the vibrations [13]. It also depends on how the exposed human is handling the tool. Individual preferences of positioning the hands and arms when holding a tool will often change the angle which the vibrations are transmitted to the fingers and hand. This will affect how the vibrations are transmitted and dissipated in the finger-hand-arm system [14]. Also, variations in grip force and push force have been shown to alter the mechanical impedance of the finger-hand-arm system. This may greatly affect the dissipation and transmission of vibration energy [15]. A higher grip force has been shown to cause a higher impedance (more rigidness) of the finger-hand-arm system [15, 16]. As a result, the apparent mass of the dynamic system increases. This could mean that instead of only the skin and flesh of the fingers and hand directly beneath the tool handle being vibrated (small apparent mass), the whole hand and fingers vibrates, more like a rigid system (large apparent mass). In this situation the vibration energy will be transmitted to more proximal body parts, such as the wrist, arm, and elbow. An increasing amplitude of the vibrations are also associated with a higher impedance of the finger-hand-arm system, but the effect is not as strong as with increasing grip force [16]. Laboratory studies have shown that higher frequencies of vibrations have the opposite effect. The apparent mass of the system is reduced, and the absorption of vibration energy is more localized to the areas near the coupling of the fingers/hand and the handle of the tool [13]. The combination of factors described above may also cause additive coupled effects. Results from a laboratory study by Aldien et al. showed that a combination of a large diameter (50 mm) grip handle, extended elbow and increase in grip or push force had a coupling effect which considerably increased energy absorption during x-axis vibration [17]. Taylor et al. showed that different hand-arm postures influenced temporary threshold shifts in VPT at equal HAV exposures [110]. These findings show how ergonomic factors may influence the vibration exposure transmitted to the hands, and plausibly affect the risk of adverse health effect in the fingers, hands, and arms.

As mentioned in section 4.2.1 the finger-hand-arm system has its own resonance frequencies. A laboratory study by Xu et al. found the resonance frequency of the upper arm to be 7-12 Hz [18] and Welcome et al. found the resonance frequency of the forearm to be in the 16-30 Hz range, the wrist and palm of hand in the 30-40 Hz range and the fingers around 100 Hz [14]. Above 50 Hz vibration emission was transmitted only to the fingers and hands. The vibration amplitude at the resonance frequencies were amplified 1.5 times in the forearm, 2.5 times in the wrist/hand and 3 times in the fingers. Such laboratory studies on the dynamic response of the finger-hand-arm system when exposed to vibrations (typically with a set-up with a vibrating cylinder representing a tool handle) has added knowledge that aids the understanding of how the different properties of vibrations contributes to health risk.

4.3 Signs and symptoms of the hands caused by vibration exposure

Vascular disorders in the fingers causing the symptom of white fingers when exposed to cold, was associated with HAV exposure by Loriga in 1911 as mentioned above. In the following years studies showed that HAV exposure could cause other symptoms such as numbness, pain, stiffness and swelling [19-21]. These symptoms have been found to develop independently of each other in individual cases. However, neurosensory symptoms occur in general earlier than vascular symptoms. A literature review and meta-analysis by Nilsson et al [5] found that at equal exposures among workers, the occurrence of neurosensory symptoms had a shorter latency with a factor of three. With a daily exposure of 5 m/s^2 A8 a 10 % prevalence of neurosensory symptoms would occur after 3 years, and vascular symptoms after 9 years.

A differentiation in the meaning of the terms signs and symptoms is useful when discussing the effects from HAV exposure. Symptoms are changes in the body which can be seen or felt by a person. Signs are changes which cannot be seen or felt by a person, but they can be detected and measured with diagnostic devices. For example, white fingers and pain are symptoms, whereas a shift in vibration perception threshold is a sign.

4.4 Hand-Arm Vibration Syndrome (HAVS)

Hand-Arm Vibration Syndrome (HAVS) is a work-related disease of the fingers caused by excessive exposure from hand steered machines, handheld tools, or workpieces. The risk of HAVS in a HAV exposed worker depends mainly on duration of exposure and magnitude of the exposure [22, 23]. The term HAVS relates to the exposure that causes the disease and is the most used term today. However, Vibration white finger (VWF) was used when the disease became a prescribed industrial disease in UK [24] and is still in use. This name relates to the vascular component of the disease. Studies have shown an exposure-response relationship between HAV exposure and the vascular symptoms of the fingers [25, 26]. However, HAVS has three disease-components: a vascular component, neurological component, and a musculoskeletal component. It is important to be aware that the three disease components described below are interrelated [27, 28]. Damage to the peripheral nerves may affect the activation of vasoconstriction and vasodilatation of the small digital arteries of the fingers, causing a dysfunction of the circulation in the arteries. Damage to the small arteries of the fingers may impede the microcirculation around the peripheral nerves and axons, causing a dysfunction of the nerves.

4.4.1 Vascular injuries

The most known symptom of HAVS are the attacks of white fingers caused by vasospasm in the digital arteries of the fingers when exposed to cold air or cold surfaces. It is not clear what all the factors causing the vasospasm are, but it is likely a combination of local damage to the endothelium of the small digital capillaries and an exaggerated sympathetic reflex causing the constriction that occludes the most superficial arteries. Thus, both a local and a central mechanism is involved where the latter also seem to be of importance [29].

The endothelium produces both vasodilator substances such as Nitric Oxide (NO) and vasoconstrictor substances such as Endothelin-1. When the endothelium is damaged this may disturb the production of these substances. A study by Rajagopalan et al. showed that patients with secondary Raynaud`s phenomenon had higher levels of Dimethylarginine which is an inhibitor of endothelial NO [30]. A study by Palmer et al. showed lower baseline levels of Endothelin-1 (50 %) among vibration exposed workers, but with a four to fivefold rise in levels when exposed to cold [31]. Neurotransmitters released from autonomic and sensory nerves are important to control vascular tone and smooth muscle functions in the peripheral arteries. Increased vasoconstriction mediated by α_1-adrenoreceptors and α_2-adrenoreceptors triggered by cold exposure also seem to play an important role [27]. In addition to the above-mentioned factors, substances such as Calcitonin gene-related peptide (CGRP), Substance P, Neurokinin A and Vasoactive intestinal peptide are known to be important mediators to vascular tone, and other factors such as platelet activation, fibrinolysis, white blood cell activation, reduced red blood cell deformability, increased viscosity and oxidative stress has also been reported to possibly play a role in the pathogenesis of the vascular injuries related to HAVS. The pathogenesis is multifactorial, very complex, and not yet fully understood [27].

The typical symptom of white fingers caused by vasospasms occur as attacks and usually last for 30 minutes or less. Rewarming the fingers and hands reduces recovery-time from the attacks and the period when the blood flow in the fingers normalizes is often accompanied with pain [16]. It is not surprising that the vascular symptoms historically received most attention from the medical field, because they are quite special. The whiteness of the skin makes the fingers look bloodless and dead, and the clear demarcation between normal skin tone and the white areas really stand out. The blanching always starts distally. Sometimes just the distal phalanx of one or more fingers. Over months and years with continued exposure, larger parts of the fingers, and more fingers are affected, and it happens more frequently. From perhaps just a few incidents during the winter, to several times a week and for some patients every day. Studies of vibration exposed workers have showed that 25 years after exposure had stopped, 40 % of those that were in the early stages of HAVS and 13 % of those in the advanced stage of HAVS had recovered [32]. Thus, more than half of the population never recovered from the symptoms. Because the vascular symptoms and pain are triggered by cold, people with HAVS report that outdoor activities such as lawn maintenance, snow removal, fishing and washing the car can be difficult [33].

4.4.2 Neurological injuries

The tip of the finger is densely innervated with nerve fibers that are crucial for humans to enable the handling of small objects and to master activities which requires precision and fine motor control of the fingers. These nerve fibers are affected by cumulative exposure for HAV causing people suffering from HAVS having problems with activities of daily life such as buttoning a shirt, tying shoelaces, closing a zipper, or opening a jar with a screw lid [8, 33]. These activities rely on the important ability of our fingers to sense size, texture, temperature, pressure, and friction of objects. These properties of objects are sensed by receptor nerve endings in our fingers. The most superficial nerve endings in epidermis (just under the skin) are the Merkel's discs which are excitable mainly in the frequency range from 0-5 Hz, and the Meissner Corpuscles which are most excitable in the frequency range from 5-60 Hz [16]. These nerve endings can sense fine touch, separate points of pressure and react to friction. Thus, they are important in spatial discrimination. The Pacinian and Ruffini corpuscles are nerve endings embedded deeper in the dermis, and the sensation information are more general and based on the number of nerve endings excited. These nerve endings are most excitable in the frequency range of 50-500 Hz [16].

It has been shown among people suffering from diabetes that low density of myelinated nerves cause sensory disturbances in fingers and toes; clinical studies show that low density of myelinated nerves seem to be an important factor also for HAVS patients and patients with Carpal Tunnel Syndrome (CTS) [34]. Experimental and clinical studies indicate that the stress from mechanical vibration cause local demyelination, axonal degradation, proliferation of non-neural cells and ultimately fibrosis in the nerves [35-37]. Takeuchi et al. [38] have proposed that such pathological changes in the peripheral nerves are due to edema caused by the mechanical stress from vibration of cells and tissues in the fingers. This view was supported by Lundborg et al. who found that vibration induced epineural edema in animal experiments [39]. A study by Hjortsberg et al. indicates injury at receptor level [40]. However, based on currently available research literature, it is most likely that demyelination is the primary lesion [37]. Animal studies have shown that vibration can cause disruption of the myelin sheath and constriction of the axon of the peripheral nerves [41, 42]. These studies showed that increasing level of the vibration, resulted in more severe disruption of the myelin sheath. Biopsies from fingers of HAVS patients showed demyelination, axonal degradation, and fibrosis in the peripheral nerves, as well as proliferation of non-neural cells such as Schwann-cells and a reduced number of nerve fibers [38, 43]. Unmyelinated nerve fibers which are important in temperature sensation were also decreased in number and size. A biopsy from one HAVS patient indicated that pathological changes in the more superficial nerves and nerve endings in the dermis preceded damage in the main nerve trunks and receptors of the deeper subcutaneous tissues in the fingers [44]. In a study by Strømberg et al. demyelination was also found in the Interosseous Nerve proximal to the Carpal Tunnel among vibration exposed workers [36]. This finding may in part explain why the symptoms in HAVS and CTS can be difficult to separate [34, 37]. Some power tools are heavy, and the manual handling of such tools cause strain to the underarm and wrist, which is a well-known risk factor for CTS. Thus, sometimes workers exposed to vibrating tools may suffer from both conditions. Therefore, it is important to consider both conditions for HAV exposed patients with sensorineural symptoms in the fingers because it may be relevant for the choice of treatment. It has been shown that vibration exposed workers diagnosed with CTS have a less favorable outcome from surgical decompression than patients with idiopathic CTS (unexposed to HAV) [35].

It is important to remember that injuries to peripheral nerves also may have effects in the central nervous system [45]. When the sensory signals from the peripheral nerves are changed, this causes a reorganization of the areas in the central nervous system that are processing the sensory signals. This can in turn influence the motor response in the hand and fingers. The outcome of this feedback mechanism is based on complicated relationships relying on many factors including age and higher cognitive functions [34].

A quantitative method to assess the function of the sensory nerves is to test the vibration perception threshold (VPT) of the fingertips. The method is described in section 5.4.2. Several studies have shown a dose-response between VPT and HAV exposure on a group level [46, 47] and also indications on an individual level [22, 23]. These studies show that the sensorineural symptoms usually appear before the vascular symptoms, and follow different paths of progression; indicating two different pathogenic mechanisms for vascular and neurologic injuries, which has been claimed plausible also by other authors [25]. However, to our knowledge cohort studies showing a clear dose-response on an individual level has not been published prior to the present PhD-project.

4.4.3 Injuries to the musculoskeletal system

Several reports exist of injuries to the musculoskeletal system among vibration exposed workers. However, most of those reports are not well documented [13]. One of the problems is the lack of controls in many of the reports. Vibration exposed workers are usually also exposed to manual labor which could be a likely explanation to the injuries. A study by Malchaire [48] examining pneumatic rock drill users and a control group of manual workers not exposed to vibration, showed significant degeneration of the Lunate bone in the wrist, and indications of degenerative changes also in the elbow joint among the rock drill users. Pneumatic rock drills are percussive tools vibrating at a low working frequency typically in the range 30-50 Hz, which is similar to the resonance frequency of the palm and wrist. The vibration amplitude can be very high, with more than one-centimeter oscillating movements at the grip area on the handle. Such high amplitude vibrations are not fully absorbed or dissipated in the fingers or hand but transmitted proximally to the wrist, elbow, and shoulder (section 4.2.4). It is plausible that prolonged exposure of this nature can affect bone and joints.

There are findings suggesting that HAV exposure can have a chronic deteriorating effect on muscles. In a study by Farkkila [49], a 2-year follow-up in Finland compared lumberjacks to unexposed controls. The results indicated reduced grip strength among the HAV exposed lumberjacks. However, there are researchers who question the lack of adequately developed methodology for tests of grip strength [50, 51]. Necking [52] found reduced grip strength among patients with HAVS compared to an age-matched control group; also in this study a reduction in muscle strength of intrinsic hand muscles was found. Biopsies of the Abductor Pollicis Brevis muscle from HAVS patients showed changes which correlated with cumulative vibration exposure indicating a direct local injury caused by the vibrations.

4.5 Diagnostics of HAVS

There is a battery of different tests used to assess the different disease components of HAVS. However, there is no widespread consensus on the diagnostic criteria and which tests should be used for the diagnosis. Pool et al. proposed in 2018 consensus criteria for diagnosing and staging HAVS based on the participation of seven occupational physicians that had been active and published work in the field over the last 10 years [50]. The methods and tests that reached consensus by Pool et al. were vibrametry, pegboard, monofilament test, finger plethysmography, cold provocation test and grading scales of symptoms.

Vibrametry is a test of the vibration perception thresholds (VPT) at the extremities and it can be used as a quantitative way of measuring sensory nerve function in the fingertips [53]. The method is standardized by the International Standardization Organization (ISO) [54]. The method is described in more detail in section 9.5.1.

Pegboard is a test of the manipulative dexterity of the fingers. The test equipment consists of a number of small pegs which are to be placed as fast as possible into small holes in a board by the patient. There are two types of pegboard tests which are frequently described in the literature: *Purdue pegboard* and *Grooved pegboard*. Both pegboard tests have been shown to be reliable [55, 56]. The method is described in more detail in section 9.5.2.

Semmes-Weinstein monofilament test (SWMT) is used to test tactile function in the extremities. A SWMT kit typically consist of 20 filaments of the same length but of varying thickness, graded according to thickness. During the test the examiner will slowly press each filament perpendicular to the skin at the pulp of the index finger and keep the pressure for 1.5 seconds and then remove the filament slowly. The procedure is applied three times for each filament, but the filaments are applied randomly. The patient signals every time she feels anything. The lightest filament that is felt by the patient is finally recorded. This method was described in a study by Suda et al [57].

Finger Pletysmography is a method of measuring the systolic blood pressure of the fingers. The pletysmograph typically uses a strain gauge or an infrared photoelectric sensor to measure the changing pulsing blood flow in the finger. The tests are carried out after the blood flow in the fingers have been occluded using a pressure cuff and the fingers have been cooled to 15, 10 or 6°C [58]. The pressure at which the blood returns to the finger is the systolic blood pressure. If the blood pressure is less than 80 % of reference data from blood pressure while fingers were maintained at 30°C, then it is an indication of pathology. If blood pressure is less than 60 % than reference, then pathology is likely [59].

Cold provocation test (rewarming time test) is a test of the time it takes for the fingers to reach normal temperature after cooling of the fingers and hands. Different protocols of this test have been reported [60]. An ISO Standard published by the International Standardization Organization have been published and can be viewed as a reasonable compromise between the protocols [61]. According to this standard the fingers are cooled down to a temperature of 12°C by immersion in cold water. Thermal sensors (thermocouples or thermistors) are attached to the fingers, and a thin waterproof glove is used to keep the fingers and hand dry. Temperatures are usually measured for the duration of a settling, immersion, and recovery period (for example 2, 5, and 15 minutes respectively). If 4°C recovery takes more than 5 minutes, possible pathology is indicated. If 4°C recovery takes more than 10 minutes, then damage to the vessels is likely [16].

The *Stockholm Workshop Scale* [62] has been a well-established method of staging the vascular symptoms of HAVS into stages 0 - 4, based on frequency of attacks, how many fingers are attacked and which phalanges of the finger. The staging is made separately for each hand. This method has later been modified, because what constituted “frequent attacks” was not described clearly in the method, and there was an assumption of a positive relationship between frequency of attacks and extent of blanching. The documentation for this assumption has been shown to be weak, and there are examples of patients with frequent attacks, but only blanching of the distal phalanges of a few digits. In the proposal for new international consensus criteria by Pool et al., two new grading scales, one for the vascular component and one for the neurological component are recommended. The staging of the vascular component has four stages based on the number of phalanges affected by blanching. The neurological component is a modification of a staging similar to the Stockholm Workshop scale that was proposed by Brammer et al. at the same workshop in Stockholm [63].

Table 1 International Consensus Criteria (ICC) for the staging of HAVS

HAVS Vascular Component	
ICC Stage	**Description**
0V	No attacks of blanching
1V	Digit blanching score 1-4
2V	Digit blanching score 5-12
3V	Digit blanching score > 12

HAVS Neurological Component	
ICC Stage	**Description**
0N	No numbness or tingling of digits
1N	Intermittent numbness and/or tingling of digits
2N	As in stage 1 but with sensory perception loss in at least one digit as evidenced by two or more validated methods such as monofilaments, thermal aesthesiometry and vibrotactile thresholds
3N	As in stage 2 but with symptoms of impaired dexterity by the Purdue pegboard test

4.5.1 Assessment of past exposure

In the assessment of a suspected diagnosis of HAVS it is important to assess the patients' exposure history. It is difficult to get an accurate exposure history because of several reasons. In many professions a worker will be exposed to many different vibrating tools, with different exposure characteristics, exposure times, and exposure levels. It can be difficult to find the exposure levels of a tool that was used perhaps more than 20 years ago. Factors such as tool maintenance and individual working techniques also has an influence on the exposure. With so many factors that influence exposure over time, this will increase the risk of recall bias. Studies have shown that workers have a clear tendency towards overestimating exposure time [64, 65]. Therefore, it is reasonable to assume that it will improve the estimates of cumulative exposure when results from measurements of representative working tasks are used as a support to the exposure history recalled by individual workers. More on the assessment of vibration exposure is covered in section 4.6.

4.5.2 Differential diagnosis

There are several conditions which may cause blanching of the digits. Raynaud's phenomenon is a commonly used term to describe these symptoms which was first described by Maurice Raynaud in 1862. Raynaud's phenomenon may be caused from mechanical or chemical exposures, or as secondary symptoms from a disease. In these cases, the symptoms are often referred to as Secondary Raynaud's phenomenon. HAVS is the most common cause of Secondary Raynaud's Phenomenon [66]. Other conditions are connective tissue diseases such as scleroderma and rheumatoid arthritis, obstructive arterial diseases often in conjunction with Diabetes, and drug intoxication whereas the most common are drugs which block the function of the beta-adrenoreceptors (involved in vasoconstriction of the capillaries). Compression syndromes such as Thoracic Outlet Syndrome and Carpal Tunnel Syndrome (CTS) may also cause symptoms that mimic HAVS symptoms. CTS can sometimes be difficult to separate from HAVS because patients may suffer from both conditions at the same time (see section 4.4.2). CTS is associated with heavy manual labor and repetitive strain to the hands and arms, which is also typical for vibration exposed individuals [67].

Primary Raynaud's disease is a hereditary disease with a 70 percent familial association and the disease manifests typically in late adolescence or early adulthood [68]. The symptoms present themselves as blanching of the fingers when exposed to cold. However, as opposed to HAVS the symptoms usually appear symmetrically, bilaterally on both hands. Some individuals may experience blanching attacks in the toes, and in rear cases also ear flips and the tip of the nose. In some cases, psychological stress can also provoke blanching attacks. The reported prevalence in a population varies between countries and climate zones. In temperate zones typically about 10 % of the population is affected, with females having a five times higher risk than men of being affected [66].

4.6 Measurement of hand-arm vibration

The quantification of energy from mechanical vibrations to be able to predict the risk of negative health effects is complicated because, as described in section 5.2, mechanical vibrations have many properties which by themselves or in combination can potentially cause damage to human tissue. In addition, exposure time and ergonomic factors are important variables which may influence transmission of vibration exposure to the hand and arm. The most important variables are listed on the next page:

1. Displacement: Mechanical vibrations are oscillations of an object around an equilibrium with a back-and-forth movement between two endpoints. The displacement of this movement is the distance between the two endpoints. Often

the term *amplitude* is used, which is the distance between midway (equilibrium) and an end point.

2. Speed (velocity): Midway between the endpoints of the vibration the speed is at its maximum. The speed is inversely proportional to the acceleration (at a given frequency).
3. RMS Acceleration: From midway (equilibrium) there is a deceleration towards the next endpoint, at which the speed is reduced to zero. The direction of the movement then changes and is followed by an acceleration towards equilibrium and a deceleration until the other endpoint is reached. RMS (Root Mean Square) is the mathematical method used to account for the vibration energy in both directions (if not used the vibration energy would be zero).
4. Frequency: The displacement from one endpoint to the other endpoint and back again is one movement cycle. The number of cycles completed in one second is the frequency in Hz.
5. Direction: The angle at which the vibration energy is transmitted from the vibrating surface to the fingers and hands affects how the vibration energy is transmitted to and propagated in -human tissue. Furthermore, a vibrating tool vibrates in more than one axis.
6. Exposure time: The duration of exposure may be estimated as a cumulative lifetime exposure and can be measured in exposure years. The duration can also be measured for a working day, which gives more information about the current exposure intensity.
7. Intermittency: The exposure may be similar from day to day, or there may more intermittent exposure with exposure-free days in between. The exposure from the vibrating tool may be of a continuous nature, such as the exposure from a lawn mower, or it may be intermittent, such as the exposure from an impact wrench.
8. Grip force: The force at which the tool handle of the vibrating tool is held during vibration exposure.
9. Push and pull -force: The force at which the tool handle or machine is pushed/pulled during vibration exposure.

10. Posture of hand, arm and body: Posture may affect the angle vibrations are transmitted to the body, which may affect how effective the vibration energy is propagated through the human tissue layers.

Many of the above-mentioned properties of vibrations and vibration exposure may be affected by individual working techniques. For example, the grip force and push/pull force may vary between workers. Also, the type of working technique might influence direction, duration, and intermittency of vibration exposure.

4.6.1 Standardized measurement methods

Despite how complex it is to evaluate mechanical vibrations in relation to the health hazards they pose to humans, it is important to have a common ground on how to deal with the problem. General requirements on how to quantify and measure HAV is described in ISO standards which are made based on international consensus between countries participating in the International Standards Organization. The two most important standards are *“ISO 5349-1 Mechanical vibration -Measurement and evaluation of human exposure to hand transmitted vibration- Part 1: General requirements”* [69] and *“ISO 5349-2 Mechanical vibration -Measurement and evaluation of human exposure to hand transmitted vibration- Part 2: Practical guidance for measurement at the workplace” [70].* These two standards are commonly used worldwide, and in Norway these two standards are referred to in national legislature as the basis for the measurement method to be used when assessing HAV at the workplace.

According to ISO 5349-1, hand-arm vibration exposure is measured as acceleration energy, using the unit m/s^2. The acceleration is calculated using the RMS (Root Mean Square) method. The HAV exposure must be calculated as a sum value based on the vibration measured in three directions, the X, Y and Z-axes. The X and Y axes are perpendicular in the same plane, and the Z-axis is perpendicular to the plane of the X and Y axes (fig 1).

The sum value is calculated with this formula:

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2}$$

Where:

a_{hw}	is the root-mean-square (rms) single-axis acceleration value of the frequency weighted hand-arm vibration, in meters per second squared (m/s^2);
a_{hv}	is the vibration total value of frequency weighted rms acceleration (sometimes known as the vector sum or the frequency-weighted acceleration sum); it is the root-sum-of-squares of the a_{hW} values for the three measured axes of vibration, in meters per second squared (m/s^2);
$a_{hwx,}\ a_{hwy,}\ a_{hwz}$	are values of $a_{hw,}$ in metres per second squared (m/s^2), for the axes denoted *x, y* and *z* respectively.

The frequency weighting (Wh) covers the frequency range in octave bands from 8 – 1000 Hz (fig 2) or alternatively one-third-octave bands from 6.3 – 1250 Hz (5.6 – 1400 Hz nominal range). Band limiting high-pass and low-pass filters restricts the effects of frequencies outside this range. This frequency range and weighting is based on assumptions about which frequencies are most potent to cause damage in the human body. The daily exposure is based on an 8-hour energy-equivalent acceleration value which brings the exposure evaluation into line with the "time weighted average" which is conventionally also used for the evaluation of human exposures to noise and chemical substances. The 8-hour energy-equivalent acceleration (vibration total) value $a_{hv(eq,8h)}$ is for convenience denoted A8. It is calculated by using this formula:

$$A8 = a_{\mathrm{hv}}\sqrt{\frac{T}{T_0}}$$

Where:

T is the total daily duration of exposure to the vibration a_{hw}

T_0 is the reference duration of 8 h (28 800 s)

If the total daily vibration exposure consists of several work operations with different vibration magnitudes, then the daily vibration exposure, *A*8, shall be obtained using this formula:

$$A8 = \sqrt{\frac{1}{T_0}\sum a_{\mathrm{hv}i}^2\, T_i}$$

Where:

$a_{\mathrm{hv}i}^2$ is the vibration total value for the *i* th operation;

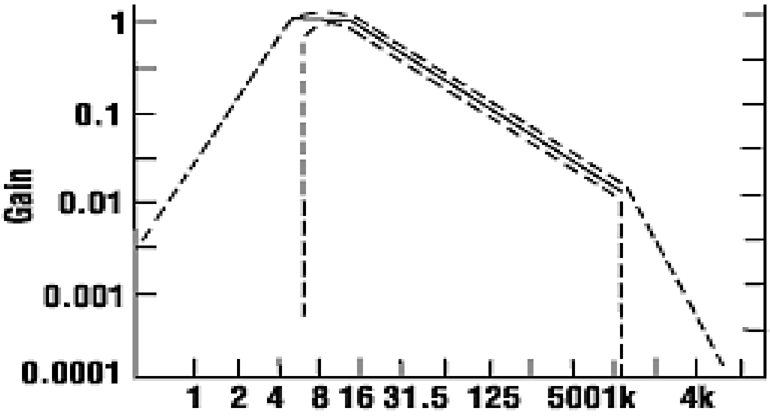
n is the number of individual vibration exposures;

T_i is the duration of the *i* th operation.

Example: If a daily exposure consists of three exposure periods from different tools with exposure times of 1 h, 3 h and 0.5 h with exposure magnitudes of 2 m/s^2, 3.5 m/s^2 and 10 m/s^2 respectively, then:

$$A8 = \sqrt{\frac{1}{8\,h}\left[(2\ \mathrm{m}/s^2)^2\ x\ 1h + (3.5\ \mathrm{m}/s^2)^2\ x\ 3h + (10\ \mathrm{m}/s^2)^2\ x\ 0.5h\right] = 3.4\ m/s^2}$$

Figure 3: The Wh weighting curve according to ISO 5349-1



ISO 5349-2 gives practical guidance and procedures for measurements at the workplace. This includes identifying typical working operations which make up a subjects normal working pattern, selection of operations to be measured, how to measure the selected operations (measurement durations, repetition, attachment of accelerometers), evaluation of typical daily exposure time and calculating the 8-hour energy equivalent vibration exposure. The standard does not define guidance on how to evaluate the effect from additional factors such as coupling force (gripping force and or feed force), working techniques or environmental conditions. which might affect the measurement result.

4.6.2 Alternative measurement methods

The Wh weighting curve puts most emphasis on the lower frequency range with a peak (weighting factor of approximately 1) around 15 Hz, and a sharp decline with a weighting factor of about 0.5 at 31.5 Hz and below 0.1 at frequencies above 160 Hz. Thus, the weighting curve used presently is indicating that the higher frequencies cause less damage to humans. This weighting curve is disputed in the scientific literature, and there is a growing amount of evidence indicating that the higher frequencies should be emphasized more [71-

73]. An alternative weighting curve has been proposed by Bovenzi et al. [74]. This weighting curve has been published (as a Technical Report) by the International Standardization Organization as a supplementary method to the Wh weighting curve [109].

Coupling force can be an important variable which may affect the transmission of vibration energy from the tool to the fingers and hand [15]. From own experience and communication with experts, it is not common for occupational hygienists to measure coupling force when assessing exposure to HAV in the workplace. One of the reasons for this may be that the currently commercially available measurement devices which can measure both HAV and coupling force are based on a hand-adaptor sensor technology. These type of sensors are attached to the palm of the hand, which is not the preferred attachment of the measurement sensor according to annex D in ISO 5349-2 [70]. However, using hand-adaptors is an alternative method which is used by companies to monitor vibration exposure among their workers. It is a convenient method because it enables monitoring of individual HAV exposure over full work-shifts by using small personal vibration exposure meters (PVEM). A new ISO standard was published in 2021 which standardizes the technical properties of a PVEM [75]. Measurements from hand-adaptors have been shown to correspond well with measurements with tool-attached sensors in a laboratory setting [76]. However, it is not known to what extent these results are reproducible under more realistic working conditions.

The standard ISO 15230:2007 defines the coupling parameters between the hands of a machine operator and the vibrating machine [77]. Parameters such as push, pull, grip and pressure exerted on the skin are defined, and informative annexes give guidance on measurement procedures for these parameters. This standardized method is not widely used among occupational hygienists or researchers. Probably because the method is complicated, and it is unknown to what extent it can help reduce the risk of vibration related injuries.

4.6.3 HAV exposure among rock drillers and impact wrench operators

There is strong evidence showing that exposure to vibrating handheld tools increase the risk of chronic injuries to the fingers and hands, such as HAVS. Dose-response relationship has been established between the vascular component of HAVS (finger blanching) and vibration exposure [1, 26, 78]. However, a dose-response relationship between exposure and the neurological component of HAVS, using vibration perception thresholds (VPT) as an objective measure has only been shown on a group level [46, 47].

Rock face stabilizers are specialized roadworkers who use rock drills as the main tool. They mount fences or nets in steep slopes and attach bolts into rock faces to protect homes and infrastructure such as roads and railways against landslides or falling rocks and ice. The vibration exposure has been reported to be very high among these workers [79] and symptoms of vibration related injuries have been reported (personal communication with workers). An obstacle for doing accurate measurements of HAV exposure from rock drilling is that workers use different techniques for operating the drill, which affects the duration of contact between the workers hands and the vibrating rock drill. Researchers have observed that when workers are operating hand-guided rock drills such as jackleg drills, they often adjust handgrips and sporadically removes their hands from the rock drill during drilling [80, 81]. Therefore, task-based measurements according to the standardized method [70] on the handles of the rock drill may be misguiding and result in measurement bias which could lead to a misclassification of exposure and the risk of HAVS.

Highway guard rail workers are specialized roadworkers who are also exposed to vibrating tools. Their main tool is a battery powered impact wrench which is used to install and connect guardrails. The impact wrench they use has a lower vibration magnitude compared to rockdrills, and the exposure time is also lower. The effect of vibration exposure for this group of workers is unknown. However, workers exposed to impact wrenches at daily vibration levels below the occupational exposure limit of 5 m/s^2 A8 and even below the action value of 2.5 m/s^2 A8, have been shown to have an increased risk of vibration related injuries [73, 82].

5. AIMS

The articles published as part of this PhD-thesis are observational studies with the following aims:

- Measure and assess vibration exposure levels for specialized roadworkers who use impact wrenches or pneumatic rock drills as their main working tool
- Assess possible dose-response relationships on an individual level between hand-arm vibration exposure and VPT at the fingertips
- Assess and compare two different measurement approaches for measurement of rock drilling with jackleg drills: Measurements with hand-attached accelerometers and measurements with tool-attached accelerometers

Research hypothesis:

1. H_0: There is no exposure-response relationship between HAV exposure from rock drilling and VPT.
   H_1: There is an exposure-response relationship between HAV exposure from rock drilling and VPT.

2. H_0: There is no exposure-response relationship between HAV exposure from impact wrench use and VPT.
   H_1: There is an exposure-response relationship between HAV exposure from impact wrench use and VPT.

3. H_0: There is no exposure-response relationship between HAV exposure from rock drills and VPT on an individual level.
   H_1: There is an exposure-response relationship between HAV exposure from rock drills and VPT on an individual level.

4. H_0: There is no exposure-response relationship between HAV exposure from impact wrench use and VPT on an individual level.
   H_1: There is an exposure-response relationship between HAV exposure from impact wrench use and VPT on an individual level.

5. H_0: There is no systematic difference between measurement results obtained with hand-attached accelerometers compared to tool-attached accelerometers.

H_1: There is a systematic difference between measurement result obtained with hand-attached accelerometers compared to tool-attached accelerometers.

6. ETHICS

The studies were approved by the Regional Ethical Research Committee of South-East Norway (approval number 2012/1031). No part of the study posed any potential harm or pain for the participants. Any important findings from the health examinations were communicated to the participants. The participants gave informed consent to participate in the study before taking part.

7. SUBJECTS AND METHODS

7.1 Subjects and background data

One of the tasks in my job as an OHS (Occupational Health and Safety) advisor in a Norwegian road and construction company was to monitor the health of workers exposed to possible hazards at work. There had been worries within the company that rock drills mainly used by rock face stabilizers had very high vibration levels. As part of an internal investigation in the company, specific questions about HAVS related symptoms such as finger blanching, and numbness was included in the health surveillance of vibration-exposed workers. Among rock face stabilizers around one third of the workers reported finger blanching when their fingers were exposed to cold. Often the blanching would appear on the worker's spare time. Numbness was also frequently reported, also by some workers who did not suffer from blanching symptoms. A cooperation with the National Institute of Occupational Health in Norway was initiated to get a thorough assessment of the related health risk. Workers from different departments of the company was included in a study for the assessment of the workers vibration exposure and possibly resulting health effects. Especially finding early signs or symptoms from vibration exposure was wanted, as this could be an early indicator of workers at risk. This could make it possible to initiate early action to combat vibration hazards not only on a general level, but also on an individual level.

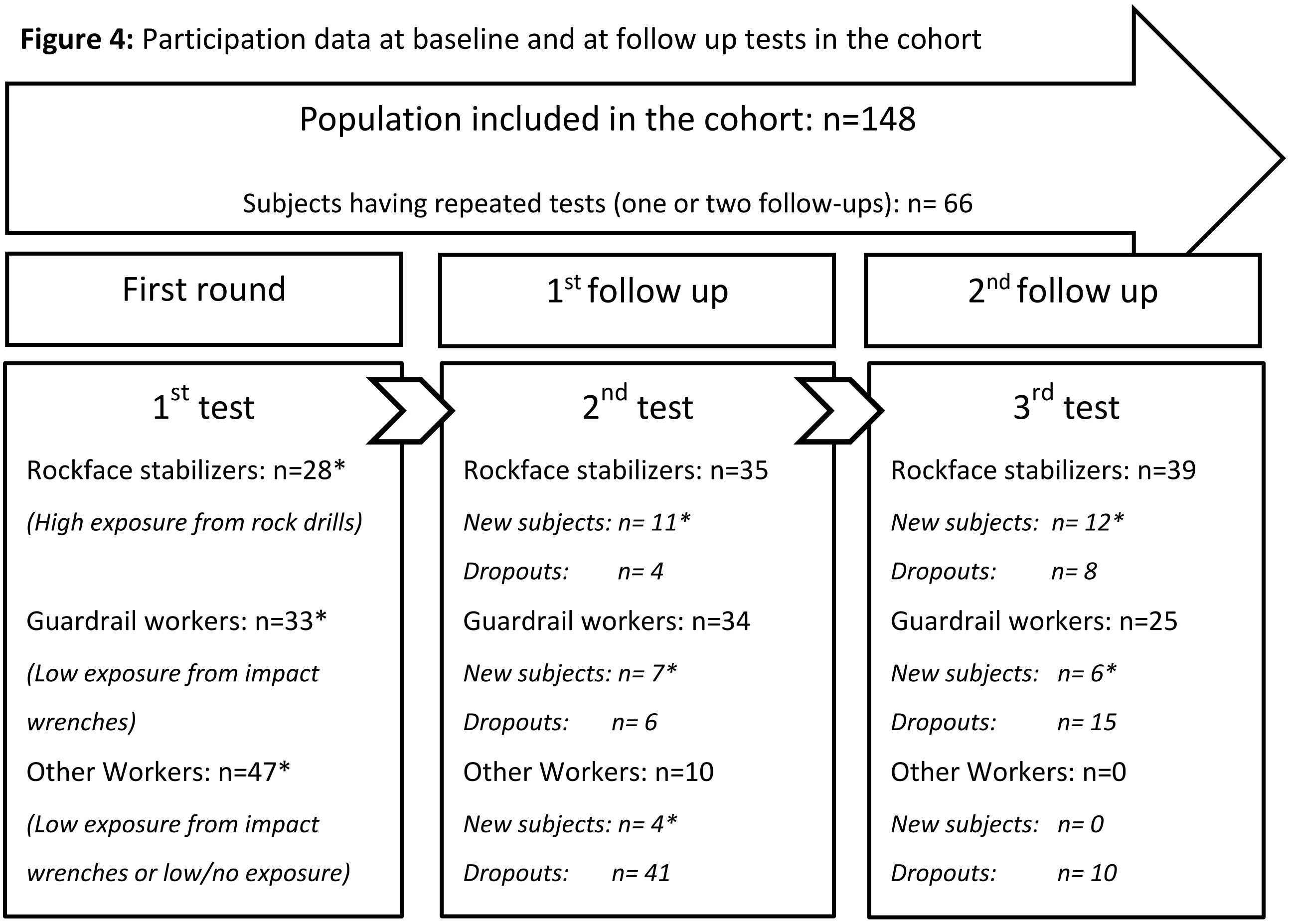
7.1.1 Subjects participating in the cross-sectional study

In a voluntary expansion of the company's health surveillance of the workers, a total of 113 subjects from different departments including a range of different work-disciplines were invited to participate in the study. The work-disciplines included rockface stabilizing workers and guardrail workers which we presumed had the highest vibration exposure. The guardrail workers use a battery powered impact wrench as their main tool and were included in the study to gain more knowledge about a presumed moderately vibration exposed group of workers, compared to the rock face stabilizers. Other presumed low or no-exposure groups including road inspection workers, electricians and machine mechanics were included as a control group. The subjects who accepted to participate formed the sample population of a cross-sectional analysis which was the base for the first publication in this thesis.

7.1.2 Subjects participating in cohort study

All subjects still working in the company who had agreed to participate in round one (the first health examination of the three in total) of the study was invited to participate in the follow-up health examinations forming the basis of the cohort study. Newly employed workers in the rockface stabilizing department and guardrail department were also invited to participate at round two and three in the study. We invited 153 workers to participate (fig. 4) in the study, 113 at baseline and 40 at the follow-up health examinations. A total of 148 workers agreed to participate. In the research population, all the workers in the highway guardrail department and the rockface stabilizing department were invited to participate (n=48 and n=53). To get a contrast to these higher exposed workers at baseline, we invited workers from other departments assumed to have low or no exposure to HAV (n=52). When we investigated the cumulative exposure (exposure history) of the participants in this group we found out that many had exposures to impact wrenches, rock drills or similar from previous work, leaving only 21 workers unexposed to vibrating power tools. Due to restructuring of human resources in the company, departments within the company were closed or sold, causing many workers to change jobs and/or leave the company. This was the main cause for many dropouts (n=41) between the baseline health examinations and the first follow-up health examinations (fig.4).

Figure 4: Participation data at baseline and at follow up tests in the cohort



Population included in the cohort: n=148

Subjects having repeated tests (one or two follow-ups): n= 66

First round	1st follow up	2nd follow up
1st test	2nd test	3rd test
Rockface stabilizers: n=28*	Rockface stabilizers: n=35	Rockface stabilizers: n=39
(High exposure from rock drills)	*New subjects: n= 11** *Dropouts: n= 4*	*New subjects: n= 12** *Dropouts: n= 8*
Guardrail workers: n=33*	Guardrail workers: n=34	Guardrail workers: n=25
(Low exposure from impact wrenches)	*New subjects: n= 7** *Dropouts: n= 6*	*New subjects: n= 6** *Dropouts: n= 15*
Other Workers: n=47*	Other Workers: n=10	Other Workers: n=0
(Low exposure from impact wrenches or low/no exposure)	*New subjects: n= 4** *Dropouts: n= 41*	*New subjects: n= 0* *Dropouts: n= 10*

*****Baseline individual test

7.1.3 Subjects participating in measurement approach study

Five experienced workers in a construction company where the cohort study was carried out, were selected based on accessibility on the planned days of exposure measurements. The workers were among the participants in the cohort study. The workers were all experienced with the handling of rock drills, and all five agreed to participate in the study.

7.2 Study design

For paper I *"Dose-response relationship between hand-arm vibration exposure and vibrotactile thresholds among roadworkers"* which was the first scientific article published as part of this PhD project, a cross sectional study design based on data from the first round of health examinations was used. A prospective cohort design was used for paper III *"Exposure-response relationship between hand-arm vibration exposure and vibrotactile thresholds among rock drill operators: A four-year cohort study"* which was the third article that was published. This paper included follow-up examinations after two and four years. Leading up to the first round of health examinations we invited workers exposed to HAV who were employed in the rockface stabilizing department and the guardrail department. We also invited presumed unexposed workers from the road inspection department. A dynamic cohort design was used and all new employees in either the rockface stabilizing department or guardrail department were invited to participate in the study during the follow-up period. As mentioned in section 8.1.2, there was a large drop out after the first round of health examinations because many in the unexposed group no longer worked in the company. In lack of a substantial unexposed group, analyses of exposure in differently exposed workers were performed.

Paper II (the second published article in this PhD project) *"Hand-arm vibration exposure in rock drill workers: A comparison between measurements with hand-attached and tool attached accelerometers"* was based on a quasi-experimental study-design. HAV exposure was measured and we observed working techniques with focus on individual hand grips during operation of rock drills in a typical working task.

7.3 Exposure assessment of hand-arm vibration using questionnaires

We used questionnaires based on the VIBRISKS protocol [83] to help estimate lifetime cumulative HAV exposures and changes in exposure during follow-up. The questionnaires included questions about daily exposure time, exposure-days per week, weeks per year and years of exposure. Additionally, questions about the use of any power tools other than the two main tools in present and previous occupational settings as well as off-work usage was included. We also looked at company work records, which we used to refine the exposure assessment for the follow-up period on an individual level. These work records showed the extent of use of portable drill rigs, which are sometimes used instead of handheld rock drills. These rigs eliminate vibration exposure for the workers when in use because they are

controlled remotely. Some workers recorded how many holes in the rock they drilled on a weekly basis over four months. We used this information to get even more precise estimates of exposure time among the rock drillers.
The main tools causing HAV exposure for the participants were rock drills and impact wrenches. Questionnaire data on exposure from other power tools were obtained and this variable was considered in models during preparation of the manuscript related to Paper I. We found no association with vibration related outcomes, and we concluded that any contribution of exposure from such other tools was too small to be a relevant exposure factor.

7.4 Exposure assessment - measurements of exposure among workers using rock drills and impact wrenches

The measurements that we did to assess exposure in the project included task-based measurements of hand-arm vibration among rock drillers (rock face stabilizers) and impact wrench users (guard rail workers). We also did measurements comparing the hand-attached and the tool-attached measurement approach (paper II) and additionally, full-shift measurements of rock drillers. Those measurements were not published (see chapter 9.1.4).

We used the task-based method in accordance with relevant parts of ISO 5349 part 1 and 2 [84] for the exposure measurements. We used the vibration meters Larson Davis HVM100 (Larson Davis, Depew, NY, USA), Svantek 103 and Svantek 106 (Svantek, Warszawa, Poland). The task-based method are measurements of the most typical work processes the workers are doing. A total of seven measurements of impact wrench exposure and 37 measurements of rock drill exposure were done. Three different types of work processes using rock drills was assessed, and work cycles were timed and counted. Based on this information we made an estimation of exposure time and vibration level. For statistical purposes, we averaged vibration exposure to daily vibration.

In the measurement protocol used in the measurement approach study, measurement cycles of 15 seconds duration of normal rock drilling operations were performed. We had five to seven consecutive measurement cycles for each worker adding up to a total of 29 cycles. We considered the 15 second measurement duration adequate to ensure

uninterrupted drilling in order to get representative samples. Simultaneous measurements were done with a tool-attached accelerometer and a hand-attached accelerometer (both of type Svantek SV105), connected to a Svantek 106 vibration meter (Svantek, 04-0872 Warszawa, Poland). Both accelerometers measured in three axes simultaneously (X, Y and Z-axis). The root mean square (RMS) value from each axis was calculated by the software program Supervisor (Svantek, 04-0872 Warszawa, Poland). The measurements were stored as pair-wise recordings of the tool-attached and hand-attached RMS acceleration. A total of 58 measurements were obtained.
Before the measurements, we asked the workers to drill a horizontal hole in a natural rock-face. This is a typical work task for the workers, and they were encouraged to perform the work according to their normal procedure, i.e., they were not instructed to perform the task in any specific way. The workers drilled holes in the same area in the rock face using an Atlas Copco BBC16W jackleg drill with a producer declared vibration magnitude of 16.6 m/s^2 and stroke frequency of 39 Hz. We chose this drill because it was the most used rock drill in the company.

One accelerometer was attached firmly to the handle of the tool by four layers of heavy-duty tape. We checked the attachment by applying manual pressure in all directions, to make sure no movement between handle and accelerometer during drilling would occur. This accelerometer was attached with the X-axis aligned with the drill rod which is also the stroke direction of the rockdrill. The other accelerometer was attached to the palm of the hand by an integrated adjustable rubber band. The accelerometers were integrated in hand adapters similar in size and shape to the accelerometer used in a laboratory study by Xu et al. [76] referred to as a type 1 hand adapter. The workers used ordinary working gloves over the accelerometer. The accelerometers were of a piezo-capacitive type not prone to DC-shifts. We checked 1/3 octave frequencies in the range range 1 Hz – 1400 Hz to identify possible 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 hand grip

We observed the workers in a separate drilling session after the measurement session to see if visible differences in hand grip on the tool handle could be observed. To assess for possible visible positional changes of the hand, close-up videos of the handgrip were recorded and reviewed in slow motion. We used slow motion video to be able to see the small changes in hand grip during drilling. Because of the fast impulses to the hand during drilling it is difficult to make good observations of this in real time. During video recording the recording angle was aligned with the axis of the tool handles and the workers did not use a working glove. With this set-up the position of the hand against the tool handle could be inspected. Videos with and without hand-attached accelerometers were recorded to clearly 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 normally work with gloves. Therefore, such measurements would have introduced uncertainty of whether they were representative of their ordinary way of working. A possible bias if removing the working glove for the measurements would be increased friction between the accelerometer and the tool handle which could cause bias in the measurement results.

7.5 Health examinations

7.5.1 Vibrametry

To the vibration perception thresholds (VPT) at the extremities we used vibrametry. This method is a quantitative way of measuring sensory nerve function in the fingertips [53]. This method is used as a diagnostic tool in several conditions where altered sensations at the extremities are among the typical signs, such as with diabetes, CTS or HAVS. The method is described by the International Standardization Organization (ISO) [54]. According to the standard, at least two frequencies should be tested: 31.5 Hz and 125 Hz and preferably both the 2nd and 5th finger of the hand, representing the Median and Ulnar nerve branch, respectively. We used a VibroSense Meter (VibroSense Dynamics, Malmø, Sweden) and tested the thresholds at seven frequencies: 8, 16, 32, 64, 125, 250, and 500 Hz. 2nd and 5th fingers on both dominant hand non-dominant hands were tested. Thus, we tested VPT at seven frequencies on four fingers for each participant. The VibroSense meter uses the method of limits (also referred to as the von Bèkèsy method) with a gradually increasing and decreasing sinusoidal vibration of a circular probe with a flat surface of 3 mm diameter. The finger to be tested rests with a light force (about the weight of the finger) against the probe during the test. A force indicator gives visual feedback to aid the patient in maintaining the correct pressure. When the test starts the probe starts vibrating with an increasing magnitude of 3 dB/s. Immediately when the test subject senses the vibration, he or she gives a signal by pressing a button with the opposite hand and doesn`t release the button before he or she can no more sense the vibration. The cycle is repeated and the vibration threshold for every frequency is calculated as the mean of four upper and lower limits of sensation. The test-retest reliability for this method was found to be high in a study where similar equipment was used [85, 86] and studies have shown it can be a sensitive method to test the progression of neurological signs related to HAVS [87, 88].

7.5.2 Grooved Pegboard Test

To test the manual dexterity of the fingers we used a Grooved Pegboard. Manual dexterity is the ability to make coordinated hand and finger movements to grasp and manipulate objects. Muscular and neurological functions are necessary to do these movements, as well as hand-eye coordination. The test equipment consists of several small pegs which are to be inserted as quickly as possible into small holes in a board by the patient. The Grooved Pegboard has pegs 2.5 cm long and 2 mm thin with a ridge along the length of the peg. The board is 12 by 12 cm and has 25 holes placed in five rows. Each hole in the board has a small groove so that the pegs must be twisted to the right position to fit in the hole. The test subject must pick up the pegs one by one and insert them in the holes as fast as possible. He or she uses one hand at a time, and the performance is timed with a stop clock. When all 25 holes are filled the test is finished. The participants were given two tries with each hand. The fastest time for both hands were recorded as the test score (in seconds). Grooved pegboard have been shown to be a reliable test [55].

7.5.3 Questionnaires

Questionnaires (see appendix 1, section 14) based on the VIBRISKS protocol [83] were used. The questionnaires included questions about symptoms such as white fingers, numbness and pain as well as questions about functional limitations and medical conditions or injuries which could influence the typical symptoms of HAVS. We also included questions about exposure history, such as daily exposure time, exposure days per weeks, weeks per year and years of exposure, in addition to questions about the use of any vibrating tool other than the two main tools in present and earlier occupational settings, including after work acitivies. At the follow up health examinations we administered questionnaires with questions about any new symptoms or changes in the workers exposure situation since the last health examination.

7.5.4 Blood samples

We analyzed blood samples from the participants in the first round of health examinations, for parameters potentially relevant to the pathophysiology of sensory nerve function. Analyses included haematology, glycated haemoglobin (HbA1c), C-reactive protein, carbohydrate-deficient transferrin (CDT), vitamin B, folate, albumin, alanine transaminase, glutamyl transpeptidase, cholesterol, caffeine, cotinine and thyroidal tests. The blood samples were taken on the same day as the baseline tests of VPT and Pegboard score. Blood was collected from the cubital vein using 8 mL Vacutainer tubes with no additives (BD Vacutainer, Belliver Industrial Estate, Plymouth, UK). Serum was separated by centrifugation at 2000g for ten minutes duration. Four samples were pipetted into 4 mL NUNC polypropylene cryotubes (Sigma-Aldrich, St. Louis, Missouri, US) and frozen and stored at the National Institute of Occupational Health in Oslo, Norway at -80°C until analysis. Blood tests were collected from only 95 subjects due to time constraints on the examination day. Measurement of CDT was done at Furst Medical Laboratory (Oslo, Norway) by capillary electrophoresis with CapillarysTM (Sebia Inc., Georgia, USA). Limit of detection for this method was 0.4 %. A level of <1.7 % was considered normal by the laboratory. HbA1c samples were collected in EDTA tubes and analyzed at Furst Medical Laboratory (Oslo, Norway). A level of 4-6 % was considered normal by the laboratory. The sample preparation of cotinine, caffeine and nicotine in serum has been described previously [89]. However, in our study we used two internal standards instead of one. To 0.5mL serum aliquots, we added 100 µl 0.0025 mg mL^{-1} internal standard solution, containing caffeine$^{13}C_3$ and cotinine (methyl-d_3). We used a Waters CapLC System (Milford, MA, USA) to separate analytes. To separate the analytes and mass spectrometric detection a Quattro LC tandem quadrupole MS with positive electrospray ionization (ESI, Micromass, Manchester, UK) was used. Nicotine, cotinine, cotinine-(methyl-d_3), caffeine and caffeine$^{13}C_3$ were monitored as product ions of their respective [M+H]+ molecular ions with m/z transitions of 163–132, 177–80, 180–80, 195–138 and 198–140. The mass spectrometric settings have been described previously [89]. Quantification of cotinine, caffeine and nicotine was done by adding internal standards and relative comparisons to spiked blank serum samples that were identically prepared. Evaluation of the methods was performed over concentration ranges of 30–20 000 µg nicotine L^{-1} serum, 7.5–15 000 µg caffeine L^{-1} serum and 1.5 to 1000 µg cotinine L^{-1} serum, showing a coefficient of correlation >0.996. The within assay (n=6) and between assay (n=6) precision for nicotine, caffeine and cotinine were <27, <36 and <11 %, respectively. The detection limit for nicotine was 31 µg nicotine L^{-1} serum; for caffeine, 2.1 µg caffeine L^{-1} serum; and for cotinine, it was 1.9 µg cotinine L^{-1} serum. The detection limit was defined as two times standard deviation of the blank.

Blood tests were not included in the follow-up health examinations, because the results from the tests did not indicate any relationships with the outcome in the study,

7.6 Statistical analysis

7.6.1 Comparison of tool-attached and hand-attached accelerometers (paper II)

For the statistical analysis of the data from the comparison of tool-attached and hand-attached accelerometers we used Stata 16 (StataCorp, College Station, TX, USA).
We calculated the mean, range, and standard deviation of the exposure variable (m/s^2) for each worker for both accelerometer placements. We did a visual inspection and comparison of the residuals with a normality plot which showed an almost perfect fit. Thus, we assumed a normal distribution of the residuals. We used mixed effect models with worker as random intercept and pairwise measurement differences between the two accelerometer

placements as fixed effect to assess mean difference between hand and tool measurements for the workers. There were no missing data, Therefore the pairwise measurement difference could be used directly as a fixed effect. We calculated intraclass correlation based on this model which gave a measure of the proportion of variability within and between workers for the repeated measurements.

We used the same mixed effect model as described above but sorted by worker as random effect to assess the mean difference between hand and tool measurements for each worker separately.

7.6.2 Cross sectional study (paper I)

Associations between HAV and VPT at baseline was investigated by using multiple linear regression models in SPSS version 25 (IBM SPSS, Armonk, NY, USA). In preparatory analysis the potentially confounding factors BMI, cotinine, caffeine, vitamin B12, free T4, HbA1c and CDT were included in the regression models for all frequencies at the dominant 2nd finger where the most significant associations were found. None of the information from the analyses of blood samples confounded the outcome. We classified age into intervals (20-29, 30-39, 40-49, 50-59 and 60-69). We kept the age variable 60-69 in the model as the analyses showed that only age at this level influenced the association (changing the estimate of effect with more than 10 %). The number of hours multiplied with the typical acceleration level ($h \cdot m/s^2$) served as the main exposure measure for the operation of the two main tools. To investigate different outcomes based on which main tool the workers were exposed to, we split the independent exposure variable in two separate variables (rock drill exposure and impact wrench exposure). We also applied the acceleration level normalized to an 8-hour working day (m/s^2 A8) multiplied by the number of days of operation for the two tools in models to investigate if the workers' exposure in relation to legislative EAV and ELV would provide any additional information. To enable log transformation, zero exposure to the main tools was substituted with $h \cdot m/s^2 = 1$. We log transformed the exposure measures to correct for skewness. Because the outcome was measured as threshold of perception in decibels, we built the models using a log-log transformed data set. Participants with injured or missing fingers were included in the analyses but only with the non-injured fingers.

7.6.3 Cohort study (paper III)

Stata 16 (StataCorp, College Station, TX, USA) was used for the statistical analysis of the longitudinal data. For the analysis of study population characteristics, we classified the study participants based on main tool exposure (rock drill, impact wrench or no/low exposure) and used descriptive statistics with population means including standard deviations. We did a preparatory analysis of the study population at baseline. BMI, cotinine, caffeine, vitamin B_{12}, free T4, HbA1c, and CDT were included in the analysis as described in paper I. None of the information from the analyses of blood samples had a confounding effect on the associations between exposure and outcome.

To answer our objective on determining a possible dose-response 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 2nd and 5th fingers. The lifetime cumulative exposure was calculated as the mean vibration magnitude from the respective tool (m/s^2) multiplied by lifetime exposure time in hours (h). We log10-transformed the exposure measures to correct for skewness. We included exposure for rock drills and impact wrenches by using separate terms in the same model, as we did when we analysed the cross-sectional data.

Separate analyses using only the last 12 months of exposure to check for possible changes in associations based on more recent exposure was also done. Thus, not taking lifetime cumulative exposure into account.

We adjusted the models for the longitudinal data for age using 10-year intervals (20-29, 30-39, 40-49, 50-59 and 60-69). We did sensitivity analyses using age and age squared in models. We excluded outliers from the final models on a finger and frequency-wise basis if their model residuals exceeded three standard deviations to avoid the possibility of outliers interfering with the results. We set the significance level at $p \leq 0.05$.

We executed all mixed model analyses both including and excluding participants who had only one test (no follow-up tests). When we included all participants there was a slightly higher and more significant effect on the association between exposure and VPT. Therefore, we included all participants in the final models. In sensitivity analyses BMI and height were included in the mixed models but we did not keep those variables in the final models because the effect on the association between exposure and VPT only changed the estimate of the association with less than 2 %. For the analysis of association between vibration exposure and pegboard score, we used the same exposure variables as described above and adjusted for age in 10-year intervals.

8. RESULTS

8.1 Group characteristics

Participation in the cohort study was accepted from 148 workers, including workers joining the study at 1st and 2nd follow ups (Figure 4). The cross-sectional analyses were based on 104 participants from the first round. 51 of 148 workers had high levels of HAV exposures from pneumatic rock drills which they mostly had used in rockface stabilizing work and 46 workers had lower levels of exposures from impact wrenches mostly used in highway guard rail work. Three workers had used both tools. Among the 51 workers from other departments (general road inspection and maintenance work assumed to have little exposure) some had previous exposure. From investigating the exposure history of the participants in this group it was found that many had exposures from previous work to impact wrenches, rock drills or similar leaving only 21 workers who were considered unexposed to vibrating tools. There was a drop out of 41 subjects between baseline and first follow-up among the no/low exposed workers because of reorganization in the company, causing many workers to leave their jobs. In the exposed groups some dropouts were caused by difficulties in scheduling the times for testing with their work rotation.

Four workers did not meet for scheduled health examinations and one worker were excluded from the study because of known diabetes type I.

8.2 Exposure assessment

The measurement results for rock drill exposure showed a substantial variation. Some measurements showed exposure levels below 10 m/s^2, whereas other measurements showed exposures above 30 m/s^2. For short durations, extreme levels above 70 m/s^2 were measured. Based on observations of the work, the most important variables contributing to these differences were different composure of the rock being drilled, and the way the workers handled the rock drills. When the rock had many cracks and loose fragments inside, the vibration level transmitted to the hand of the worker would often increase. This was observed especially in situations where the drill rod got stuck in a crack inside the rock. In situations where the worker tried to pull the rock drill loose, extreme levels above 70 m/s^2 was measured. In preparatory analyses we also performed full shift exposure measurements with hand-attached accelerometers, in addition to the standardized method using tool-attached accelerometers. With the full-shift measurements we could better monitor the changes over a work shift, and the idea was also to get better control over the uncertainty related to individual handling of the rock drills. The full shift measurements gave important insight about typical exposure patterns among the rock face stabilizers. However, because the measured vibration magnitude seemed to be considerably lower when using the hand-attached accelerometers as compared to the measurements with the tool-attached accelerometers we designed a separate study to investigate these differences. Based on the uncertainty related to using hand attached accelerometers for assessing vibration magnitude, the full-shift measurements were used for guidance to better estimation of exposure times. Based on measurements in the workplace, we estimated HAV exposure from rock drills to an average vibration magnitude of 17 m/s^2 (range: 3 – 58) and from impact wrenches an average magnitude of 7 m/s^2 (range: 5 – 8). These numbers corresponded well to typical levels measured for these type of tools [90]. Based on the time measurements and interviews with workers, the average exposure time for rock drill use was estimated to 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 m/s^2 (A8) for rock drilling and 1.2 m/s^2 (A8) for impact wrench use. The variation in exposure from day to day was high, especially for the rock face stabilizers with HAV exposure on about half of the working days during a year. Table 3 was not published in any of the publications and gives a more detailed overview of the estimations of HAV exposure for the rock drill operators.

Table 2: Partial and total exposures in rockface stabilizing work

Equipment	Average vibration amplitude (range)	Average daily exposure time**	Number of measurements
Rock drill with handjack	16 m/s^2 (12 – 20)	20 min.	8
Rock drill with jackleg	16 m/s^2 (7 – 36)	15 min.	12
Standard rock drill with vibration dampening weight attached to handles	14 m/s^2 (3 – 27)	6 min.	10
Standard rock drill without vibration dampening or iron weight	33 m/s^2 (17 – 58)	3 min.	7
Other tools*	10 m/s^2	3 min.	-
Total for all tools:	17 m/s^2 (3 – 58)	47 min.	37

*Estimated
** Exposure times for the use of vibrating tools varied substantially and about half of working days were exposure free. Exposure time was averaged over all workdays.

8.3 VPT from cross-sectional data in round 1 (paper I)

VPT increased with exposure on a group level, for all tested fingers and frequencies. The rock drill operators had the highest VPT. The impact wrench operators had higher VPT for all tested fingers and frequencies compared to the workers not exposed to any of the two main tools (Table 2, Paper I). Variables based on information of self-reported lifetime use of other vibrating tools did not show any associations with the outcome (not shown). Age 60-69 was the only variable shown to have an impact on the effect estimates among the variables we tested for possible confounding effects.

8.3.1 Effects at the individual level between cumulative exposure expressed as m/s^2 multiplied by hours of lifetime exposure, and VPT

A statistically significant association between increasing vibration exposure and elevated VPT was found for all seven frequencies on both the dominant 2nd and 5th finger, on the non-dominant 2nd finger and five frequencies on the non-dominant 5th finger (Table 3, Paper I). When we used different measures of product of time and acceleration levels, we found a slightly higher explained variance in the models using acceleration (m/s^2) multiplied by the cumulative hours of lifetime exposure calculated as two independent variables compared to using the combined exposure for the two tools in the same variable (Table 3, Paper I). The two independent variables were one for exposure to rock drills and one for exposure to impact wrenches (tables 6a and 6b in supplementary material, Appendix 2, 15.1). The results indicate exposure-response on an individual level between HAV exposure and increased VPT.

8.3.2 Effects at the individual level between cumulative exposure expressed as m/s^2 A8 (daily exposure) multiplied by days of lifetime exposure, and VPT

When we used the average daily exposure level (5.4 m/s^2 A8 for rock drills and 1.2 m/s^2 A8 for impact wrenches) multiplied by lifetime days of exposure, then we found similar results for rock drills and somewhat weaker estimates of associations for impact wrenches, compared to using lifetime hours multiplied by m/s^2. The m/s^2 A8 exposure measure is what is used worldwide as basis for setting legislative action and limit levels for daily exposure. We found associations in dominant 2nd finger at all seven test frequencies for rock drill operators and at four frequencies for impact wrench operators (Table 4, Paper I). Results from all four test fingers can be seen in table 7a and 7b in Appendix 2, 15.1.

8.4 VPT from the repeated measurements (paper III)

A statistically significant exposure-response relationship between increasing cumulative vibration exposure from rockdrills and VPT was found for several of the tested fingers. The 2nd 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 we found significant associations at least at three frequencies (Table 2, Paper III). A statistically significant association was found also when using only the last 12 months of exposure as the exposure variable. We found a tendency of stronger associations at the higher frequencies with significant associations at 500 Hz for all four tested fingers (Table 3, Paper III).

We did sensitivity analyses which showed that the association was clear when including all participants (n=148) but also when including 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.

There was also a clear tendency towards an association between exposure to impact wrenches and VPT (Table 6 and 7 in supplementary material, Appendix 2, Paper III). These results were not statistically significant.

8.5 Grooved Pegboard Test results from the repeated measurements (paper III)

Our analyses showed a paradoxical significant association between pegboard score and exposure to rock drills using dominant hand (Table 4, Paper III) and between last 12 months of exposure and pegboard score using non-dominant hand (table 8 in Appendix 2, 15.3). The improvement in pegboard score was less than 2 % (about 0.7 seconds) per unit of tenfold increase in exposure. There were no significant associations between pegboard score and exposure to impact wrenches (tables 10-13 in Appendix 2, 15.3). There was a significant age effect showing a strong worsening pegboard score for the age groups above 39 years, independent of the exposure variable.

8.6 Comparison of measurements using hand-attached and tool-attached accelerometers (paper II)

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, Paper II) for four of the five workers.

The measurements with the tool-attached accelerometers showed a mean vibration level of 28.5 m/s^2 (range between individuals: 21.9-34.4). The measurements with the hand-attached accelerometers showed a mean vibration level of 19 m/s^2 (range: 10.5-31) (Table 1, Paper II). By using mixed effects models, we found this difference (9,5 m/s^2) between tool- and hand-attached accelerometers to be significant ($p<0.05$) (Table 2, Paper II).

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

We found a reduction in measured acceleration from the tool-attached accelerometers to the hand-attached accelerometers ranging from 8 % in worker 1, to 49 % in worker 3 (calculated from the coefficients in Table 1, Paper II). The measurements in the X, Y and Z axis from the tool-attached accelerometers showed a mean spread of acceleration energy of 72 % in X-axis, 12 % in the Y-axis and 16 % in the Z-axis. In the hand-attached accelerometers the measurements showed a mean spread of 40 % of the energy in the X-axis, 19 % in the Y-axis and 41 % in the Z-axis (Table S1, Appendix 2, 15.2). There was a smaller standard deviation in the measurements with the tool-attached accelerometers in all three axes compared to the measurements with the hand attached accelerometers (Table 3, Paper II). All five workers kept their hand in contact with the tool handle during the measurements.

8.7 Observations of type of hand grips (paper II)

Three different ways of gripping the handle of the rock drill were identified as typical during the observation of working technique during drilling:

1. Closed grip with palm of the hand and fingers flexed around the tool handle (Figure 2, top, Paper II). In this situation the hand and fingers vibrated together with tool handle.

2. Fingers flexed around tool handle without contact between palm of hand and tool handle. In this situation the fingers vibrated together with the tool handle. It can be clearly seen in Figure 2 middle (Paper II) that there was no contact between the accelerometer and the tool handle.

3. Open grip with slightly extended fingers. In this situation the tool handle vibrated within the hand. With this grip less vibration energy is transmitted to the fingers (Figure 2 bottom, Paper II).

It was reported by some workers (personal communication) that it was quite normal to change handgrip during a drilling operation.

8.8 Results from whole shift exposure measurements (unpublished)

Measurements over whole working shifts using hand-attached accelerometers were done, but the results were not included in the publications. The reason is discussed in the discussion section (section 9.1.4)

Table 3: Twenty whole shift exposure measurements with hand-attached accelerometers

	N	Mean	Range	SD
Vibration magnitude exposure to right hand (m/s^2)	20	14	14 (8 - 22)	3,33
Vibration magnitude exposure to left hand (m/s^2)	20	13	11 (9 - 20)	3,07
Exposure time right hand (minutes)	20	72	135 (20 - 155)	37,15
Exposure time left hand (minutes)	20	66	120 (5 - 125)	36,7
Daily vibration right hand (m/s^2 A8)	20	5	6,1 (2,7 - 8,8)	1,58
Daily vibration left hand (m/s^2 A8)	20	4,6	5,6 (1,4 - 6,9)	1,64

9. DISCUSSION

The assessment of HAV exposure and the possible clinical consequences is complex and multidisciplinary, as mentioned in the introduction. There are variables which may introduce uncertainty into an assessment, both on the exposure assessment and on the outcome assessment.

9.1 Main findings

9.1.1 Cross sectional study

Out of the 104 workers participating in the study 33 were exposed to HAV from rock drills, 52 to HAV from impact wrenches and 19 workers had no HAV exposure from these tools and low or no exposure from any other vibrating tools. There was a higher incident of vascular and neurological symptoms in the fingers among the workers exposed to rock drills compared to the workers in the lower exposed groups. Exposure to rock drills and impact wrenches was found to be associated with elevated VPT for all seven test frequencies in the 2nd and 5th finger of both hands. We found a statistically significant relationship for all tested fingers and frequencies on an individual level, except at 32 Hz and 64 Hz on non-dominant 5th finger. When we used the daily exposure measure m/s^2A8 ($5.4 m/s^2A8$ for rock drills and $1.2 m/s^2A8$ for impact wrenches) multiplied by lifetime days of exposure instead of m/s^2 multiplied by lifetime exposure hours, there was also an association with VPT, but the association was weaker. We found a stronger association with the cumulative exposure for rock drills compared with impact wrenches. We also found a stronger association for the 2nd finger compared with the 5th finger.

9.1.2 Cohort study

Among the 148 workers participating in the study, 51 were exposed to HAV from rock drills used in rock face stabilizing work and 46 were exposed to HAV from impact wrenches used in highway guardrail work. Among 51 workers in the highway inspection and maintenance departments assumed to have low exposure, only 21 workers were considered unexposed to HAV. A total of 66 workers contributed with repeated tests (one or two follow-up health examinations).

We found a significant exposure-response relationship on an individual level between HAV and VPT at 16 out of 28 test frequencies. We found the highest elevation (worsening) in VPT at the 500 Hz test frequency with 1.54 dB increased VPT per 10-fold increase in cumulative exposure. There was no reduced pegboard score associated with HAV exposure among the workers.

9.1.3 Exposure study with hand-attached and tool-attached accelerometers

We found a statistically significant difference of $9.5 m/s^2$ in vibration magnitudes between measurements using tool-attached accelerometers, compared to measurements using hand-attached accelerometers. The latter method showed a lower vibration magnitude for all workers (range of difference: $2.3 – 14.6 m/s^2$). The variation in measurement results were larger between workers than within workers (ICC = 0.68). The finding of three distinct individual type of handgrips is a plausible explanation for the between workers variation.

9.1.4 Unpublished results from exposure measurements

HAV exposure was measured over whole work shifts for a total of 20 workers working on different rock face stabilizing work where they used different types of rock drills during the shift (Table 3). The measurements were done with Svantek SV103 vibration meters with hand-attached accelerometers in both right and left hands. The mean vibration level the workers were exposed to was 14 m/s^2 (8 – 22) for the right hand and 13 m/s^2 (9 – 20) for the left hand. Exposure time varied much, from only 5 minutes up to more than 2 ½ hours. The average daily vibration level was 5 m/s^2 A8 (2.7 – 8.8), which is equal to the present exposure limit value. In 10 of the 20 measurements, the HAV exposure for the workers exceeded the ELV.

The drilling was done with hand jack drills or jack leg drills and the exposure was transmitted from the handles of the drill -or the hand jack- to the fingers and hands of the worker. Measurements and observations which we performed to validate the whole-shift measurements showed that another variable came into play, which had an important impact on the measurements. This variable was the workers individual working technique. More specific: How the workers laid their hands and fingers on or around the tool-handles. The difference was large and significant as was shown in Paper II. Because of these findings, the whole shift exposure measurements were not used directly as part of the exposure assessments. They were used as guidance and example values during the assessment process of typical exposure times. Exposure times on the days of rock drilling was on average 72 minutes (right hand). This is lower than the exposure time used for the study which was 94 minutes on the days of rock drilling (averaged to 47 minutes because half of the working days were exposure free). One of the reasons for this difference could be that exposure time was based on a cut off at 5 m/s^2 in the exposure logging files, which is quite high.

The measured exposure magnitude of 14 m/s^2 was lower than our estimated 17 m/s^2 because the hand-attached accelerometer is not always in contact with the vibrating surface during operation of the tools. However, how much this factor affects the measurements is not known. Paper II highlights how hand-attached accelerometers cause uncertainty in the measurements.

One interesting observation from the whole shift measurements is that exposure time and exposure magnitude is about the same for right and left hands of the rock drill operators.

9.2 Methodological considerations: Validity, strengths, and limitations

9.2.1 Selection bias in cross-sectional and cohort study

The selection of participants included all workers in two departments in the company, the rock face stabilizing department, and the guardrail department. Workers from other departments assumed to have low or no HAV exposure was also invited to participate. Those workers were selected based on geographical accessibility. More than 95 % of the invited workers showed up for the tests in the first round. The reason for this high attendance is probably because the tests were performed as a voluntary extension of the company`s routine health screening program, which is mandatory according to Norwegian labor laws. All workers exposed to vibrations or other potentially harmful factors in the work environment has the right to follow a regular health screening program. The high attendance is a strength of the study because we did not have to worry about a situation where a large proportion of the workers would not want to participate. This could have caused a selection bias in our research project. The “healthy worker effect” is also a possible selection bias which represents a bias we did not have any control over. More about this is discussed in section 9.2.5.

The cohort study was a continuation of the cross-sectional study, with two follow-up health examinations (including VPT tests and pegboard tests) after two and four years. Any new employees in the rock face stabilizing department and guardrail department were invited to participate during the follow-up period. A limitation of the study was the large drop out before the first follow-up health examination in the no/low exposure group. The reason for this drop-out was a re-organization in the company. It is possible that this large drop out influenced the results because the exposure contrast among the workers with repeated tests was smaller than what was planned for. This may have washed out the significant relationship between VPT and exposure to HAV from impact wrenches found in the cross-sectional study. In the cohort study the results were still indicating a relationship, but the relationship was not statistically significant. However, the main findings of a significant exposure-response effect among the highly exposed workers were confirmed in the cohort study.

9.2.2 Measurement approach study comparing hand-attached and tool-attached accelerometers

The five workers participating in this study were selected based on accessibility on the planned measurement days. Even with few participants the study documents how the measurement procedure and method of attaching the accelerometer may cause potential bias in exposure measurements. Despite the small study population, we found a trend in the difference between measurement results with tool-attached and hand-attached accelerometers. The observations of the five workers revealed examples of individual gripping techniques which could serve as explanations for possible misclassifications of exposure caused by choice of measurement procedures in studies of exposure-response associations of vibration-exposed workers. Knowledge from this study could thus help to improve estimates of HAV exposure and thus, assessments of exposure-response relationships among HAV exposed workers.

9.2.3 Measurement bias in cross-sectional and cohort study

There are several possible sources of uncertainty which may have influenced the HAV exposure measurements. Rock drills are obviously influenced by the composition of the rock being drilled. Very hard rock formations can increase HAV exposure because very little vibration energy is absorbed in the rock when it is being drilled. Counter intuitive perhaps, rock containing loose fragments and cracks can also increase HAV exposure. This is because the drill rod frequently gets stuck under such conditions. When workers try to free and retract the drill rod, they report very high HAV exposures, in addition to high physical strains. These very high HAV exposures have been measured and documented earlier [79]. Impact wrenches can also be influenced by factors in the work environment. For example, when deassembling installations such as old or damaged highway guardrail. Then tension in the structures or rusty bolts are likely to increase vibrations. Also, rock drills and impact wrenches may be influenced by age and condition and characteristics of auxiliary parts of the tools such as the size/diameter of the drill rod or the mouthpiece (for the nuts). The possible influence of all these factors makes it difficult to do measurements which are representative of typical exposure. If exposure assessment is based on just a few measurements it is possible that conditions which causes high exposures are missed in the assessment, causing a bias towards underestimating exposure levels. Likewise, if by chance the measurements were done during rare conditions with very high exposures, a bias towards overestimating exposure is also possible. It demands a sufficient number of measurements which includes all these factors in realistic proportions. It is also important to include many workers, as the work technique may differ between workers and most likely will affect individual exposure [79]. The exposure assessments were based on 37 measurements under different environmental conditions, and different tools and workers were represented in the assessments. Therefore, it is plausible that the exposure assessment represents a good estimate of average exposure among the workers, but it is not possible to achieve an accurate exposure estimate on an individual level. Therefore, some uncertainty related to individual exposure remains. However, this effect is random. Thus, if this has an influence on the results in the cross-sectional and cohort study, it has most likely diluted the effect estimates of the individual association between cumulative exposure and VPT. However, our exposure measurements corresponded well to typical levels measured for these tool categories [90].

In addition to possible bias concerning the exposure assessments, errors in relation to the effect testing (diagnostic tools) must be considered. The Vibrosense Meter used for the VPT testing were calibrated according to protocol, and the test method was based on a standardized method [54]. This method is also called the von Bekesy method, or method of limits and is the same principle as the method used for hearing tests and are often referred to as quantitative sensory tests (QST). The test results are shown in a vibrogram where the threshold level at the different test frequencies can be shown, very much like the audiogram showing the results from a hearing test. However, it can be argued that the VPT test is not purely quantitative, because it is based on subjective feedback from the patient. Even though it is a simple feedback system where the patient only must signal when he/she can sense an exposure (sound or vibration), it may differ individually on how much the sensation is affected by cognitive factors in addition to the pure mechanical exposure. However, the reliability of this method is high [85, 91] and it has been shown that VPT testing is a more sensitive method for differentiating progressive signs related to HAVS, than nerve conduction studies, despite this being a fully objective measurement method [87, 88].

It has been shown that finger temperature influences vibration perception thresholds [86]. According to the standardized method of testing VPT the temperature of the finger pulp should be above 26 C°. When we tested VPT the testing rooms always had room temperature. Different pulp-temperatures between individuals and between tests could be the cause for random error which could dilute the associations. However, it would probably not have any systematic influence and thus not cause any bias.

It has been shown that vibration exposure has a short-term effect on VPT [92-94]. There are indications of a normalizing in VPT 30 minutes after exposure [92]. In our testing protocol for VPT most workers were expected to be unexposed before testing on the test day, and no workers were exposed less than three hours before the test. However, it is possible that prolonged HAV exposure at work demands a longer time for the nerves to recover. We did not have further information about the length of the exposure-free periods the workers had before testing. It is possible that short-term effects could have caused a bias towards higher (worse) VPT at the baseline examinations, affecting the results in the cross-sectional study. It may also have contributed to a strengthening of the associations in case the tools with the highest impact on long term VPT also has the highest impact on the short term VPT.

However, it may also have diluted the associations found in the cohort study as the exposure free period before testing VPT was random.

9.2.4 Measurement bias in measurement approach study comparing hand-attached and tool-attached accelerometers

Measurement uncertainty, or random error related to the software and the hardware of the measurement equipment is low. The vibration meters used in this project fulfills the technical requirements of the instrument standard ISO 8041-1 and 2 [75, 95]. However, the place of attachment and method of attachment of the accelerometer is a potential source of bias. This potential error and how it may affect exposure measurements are the main topic for the measurement approach study (paper II).

The focus of this study is on the bias that may arise from the placement of accelerometer when measuring HAV exposure. The study indicates that on a group level there is a clear bias towards an underestimation of exposure when measuring with hand-attached accelerometers using results from tool-attached accelerometers as the reference. However, this bias is strongly connected to the individual working technique of the worker. For one of the workers, who held the handles of the rock drill in a tight grip, there was good compliance (only a small underestimation) between the two accelerometer placements, which is in accordance with the laboratory study by Xu et al. [76]. As observed in paper II, the tool attachment will in many situations measure a vibration level which is higher than the actual exposure because the hands of the workers are not always in contact with the hand grip on the hand-steered tool, while the accelerometer will measure the tool vibrations uninterrupted and “unaware” of whether there is contact and thus vibrations transmitted to the fingers and hands of the worker. Therefore, the true exposure may lie in between the two measured values from the two attachments. The measurement approach study shows very clearly how large this measurement bias may be. However, there were too few test-subjects to know to what extent this bias affects measurements on a group level. Is it larger or smaller than the 50 % difference indicated by the results in the study? It would have been useful to repeat the measurement set-up in paper II on a much larger group of workers and on different tools. This could give more knowledge of what individual working techniques are most common, and thus help giving better estimates of true vibration exposure on a group level.

9.2.5 Bias from confounding variables

The healthy worker selection bias is a well-known bias connected to occupational research. It is plausible that this effect has influenced the results also in our studies. The workers in the rock face stabilizing department who had the highest vibration exposure also must handle heavy tools weighing more than 20 kilos. Sometimes they need to climb rockfaces with ropes to access the working area and they do this in all kinds of weather. Most people will not even think of trying this kind of work if they don’t feel strong and healthy. And workers who start with this kind of work are likely to find a different job if they start to experience symptoms of disease. This phenomenon can cause bias towards underestimating the harm made from occupational exposures. The results in the pegboard test where cumulative exposure to HAV seemed to improve performance in manual motor skills (dexterity) of the fingers could be the result of a healthy worker selection effect. Perhaps some of the workers who start having problems with the manual handling of tools and objects at work are more likely to change work, leaving the remaining workers as healthy “survivors” who are more resilient against HAV exposure. This shift in the study population could possibly explain the observed paradoxical improvement in pegboard performance.

The healthy worker selection bias could also have a similar effect on the association between HAV exposure and VPT. However, probably not as much because worsened VPT is a sign and not necessarily a symptom that comes to the attention of the worker. It may not be noticed at the early stage and most likely worsened VPT precedes symptoms such as reduced manual dexterity which will worsen pegboard performance [5]. Thus, it is possible that an association between HAV exposure and pegboard performance would have been found at a later stage if the observation time of the study had been prolonged.

Recall bias is also a well-known effect. Workers tend to over-estimate exposure time when asked to recall previous work exposures [64, 65]. The result of this is that research literature which base assessments of cumulative exposure on self-reports may underestimate the effects from exposure, as the true exposure times may have been shorter than what was reported. In our study we tried to reduce the possibility of recall bias by being very specific about the definition of exposure time when handing out the questionnaires (exposure time is the duration the fingers or hands are in contact with tool while it vibrates, and not the total time used to handle the tool). We also used an alternative exposure measure, using only the last 12 months of exposure. For this period, we had good knowledge of the exposure from concurrent exposure measurements and information from company records about tool use. This enabled us to do adjustments of the exposure assessments on an individual level.

The time of day the VPT and Pegboard tests were performed was not included as a variable in the analyses. Little is known about the possible effect of diurnal variations on VPT and Pegboard score. However, there is some evidence that diurnal variations affect nerve conduction velocities. A reduction which is highest among CTS patients when tested at night time has been shown [96]. If there is such an effect influencing the tests performed in the morning vs the effect in the afternoon, this effect would be random and plausibly dilute the effect estimates in the study. The learning effect is also a possible bias related to tests that in part relies on human performance and active cooperation. This is not a probable cause of bias in our studies because repeated VPT testing with at least half a year interval between testing have shown high reliability with no apparent learning effects [91]. Grooved pegboard tests have also shown a high reliability [55] and no reports of learning effects when repeated at similarly long intervals.

Regarding the performance in the pegboard test the age effect is very strong. Our findings were in line with the study by Ruff and Parker [55]. In our mixed model analysis of associations between lifetime cumulative exposure from rock drills and pegboard score using right hand, we found a significant improvement of 0.7 seconds in pegboard score per tenfold increase in lifetime cumulative exposure. As the constant in the model was 57.4 seconds, it is an improvement of less than 2 %. This is indeed a small improvement compared to the 30 seconds (more than 50 %) worsening in score from the effect of age. VPT are also negatively affected by age [97-99]. However, we found this effect to be non-linear with a relatively flat curve until 60 years. This non-linear relationship has also been found in other studies. In a study by Seah et al. [100] there was no age effect before 60 years of age. In a study by Ekman et Al [86] the association between VPT and age was relatively flat for several test frequencies until 50 years, followed by a strong association after 50 years. Based on our sensitivity analysis we included age variables with 10-year intervals to get the best fit in the model and reduce the confounding effect from age.

In the blood samples we screened for possible confounding variables such as alcohol intake (CDT), tobacco use (cotinine), diabetes (HbA1c), hypothyroidism (free T4) and vitamin B12 deficiency. Alle these conditions may give similar symptoms as HAVS. However, none of these variables did confound the associations between exposure and outcome.

Carpal Tunnel Syndrome (CTS) is a differential diagnose which may cause a worsening in VPT [101] and thus a potential confounding variable (see section 5.5.7). It is well known that manual work and handling of heavy objects increase the risk of CTS [102]. CTS is also associated with vibration exposure [103] and low frequency vibrations from chipping hammers (similar vibration characteristics as from rockdrills) have been shown to cause nerve damage proximally to the carpal tunnel [36]. Vibrating tools are often heavy and in many types of jobs, such as in the construction industry they are used in conjunction with other strenuous manual job tasks. Therefore, it is possible to be affected by both conditions concurrently. In our study the focus has been on the association between cumulative vibration exposure and VPT and pegboard score. Whether the cause of the association in fact is related to HAVS or perhaps the differential diagnose CTS (or both) have not been studied in detail and is not within the scope of this study. However, it is very important to differentiate regarding treatment because treatment for HAVS and CTS differs. CTS patients can usually go back to pre-injury duties at work after a successful treatment which most commonly consists of a surgical release of the carpal ligament, whereas this treatment has no effect on HAVS. HAVS patients must avoid HAV exposure permanently to avoid a progression of symptoms.

9.2.6 Internal validity

We planned the study in order to limit the effects of random errors, bias and confounders. We did not find any confounding variables except for age (age group 60-69), which we included in the mixed models. We therefore believe that internal validity of the cross sectional and the cohort study is high. However, it is still possible that there are unmeasured confounders affecting the results. It is important to be aware that there will be variations on an individual level. The different symptoms related to HAV exposure seems to develop independently of each other, and there is variation in which symptoms precedes the other, even though neurological symptoms usually precede the vascular symptoms. Probably there are individual differences in susceptibility to HAVS, also stated by other authors [34, 35]. This may arise from physiological reasons; some subjects can endure more HAV exposure before onset of adverse effects happens. It also may arise from the difference in working techniques which results in differences in HAV exposure between workers doing the exact same job. Such confounding cannot be adjusted for in the modelling phase.

9.2.7 Generalization and external validity

The main exposure factor are the tools being used with their inherent vibration characteristics and the exposure time. Therefore, any type of job where the same kind of tools are used for the same duration, it is to be expected the vibration exposure is similar on a group level. The way the tools are used and the materials the tools are processing are of course important influences and cause much variation on an individual level, but the one most important factor is the tool. Therefore, any profession with extensive use of rock drills or impact wrenches are expected to have relatively similar exposures. The exposure levels from rock drills have been assessed in several studies, and the exposure levels were in the range from 18 – 24 m/s^2 (Table 3). Most of these studies assessed rock drilling in mining and quarry work.

Table 4: Exposure levels in rock drilling

Author/year	**Number of measurements**	**Occupation**	**Exposure level AM (range)**	**Reported exposure time**	**Exposure time to reach maximum allowed daily exposure level (5 m/s^2 A8)***
Bovenzi 1994 [1]	N = 5	Quarry drillers	19.1 m/s^2 (14.7-21.6)	240 minutes	33 minutes
Clemm 2014 (report) [79]	N = 15	Rock face stabilizers	20 m/s^2 (6.5-36.3)	82 minutes	30 minutes
Phillips et al. 2007 [104]	No info	Miners	21.9 m/s^2	-	25 minutes
Brubaker et al. 1986 [105]	N = 26	Miners	19.5 m/s^2	90 minutes	32 minutes
Niekerk 2000 [81]	N = 11	Miners	24 m/s^2 (SD = 14 m/s^2)	240 minutes	21 minutes
Griffin et al. 2003 [26]	No info	Quarry drillers	18.4 m/s^2 (17.0-19.5)	-	37 minutes

* The amount of exposure minutes to reach the exposure limit (legislative exposure limit in Norway, UK and EU-countries) based on the measurement results in the table.

In a study by Brubaker [105] the average reported exposure time was 90 minutes (the method for estimation was not described), In the report by Clemm [79] the average exposure time when rockdrills were used was 82 minutes (based on self-reports and time studies). Bovenzi [1] and Niekerk [81] estimated around 240 minutes (based on self-reports). In all these studies the workers would (on average) exceed the daily exposure limits. The exposures in the studies mentioned above were similar to that of the rock face stabilizers who was the highest exposed group in our study. Our assessment found an average exposure amplitude of 17 m/s^2 and average daily exposures of 47 minutes. This equates to 5.4 m/s^2 (A8) daily exposure which is higher than the occupational exposure limit level in EU of 5 m/s^2 (A8). Our estimates of 17 m/s^2 exposure amplitude is somewhat lower than the 75th percentile of 20 m/s^2 in a collection of several exposure measurements of rock drilling presented in annex B of the guidance document HAV Good Practice Guide [90]. It is possible that our measurement was a little lower because of a positive "study-effect". During the project the importance of a good working technique caught attention among the rock face stabilizing workers, and this might have lowered the HAV exposure we measured. Therefore, it cannot be ruled out that the exposure levels in general were a little higher before the project started and thus, an underestimation of cumulative exposure among the rock face stabilizers might have occurred.

Nevertheless, the vibration exposed population in our study have had similar exposures as in many other professions around the world. As discussed above, the rock face stabilizing workers in our research population were considered strong and healthy because of the physically demanding job. It is possible that this group of workers is a selected group among rock drillers which are healthier than the average worker operating similar equipment. However, this apparently did not protect them from adverse health effects from hand-arm vibrations. We believe the rock face stabilizing workers are a representative sample of rock drillers in general, when studying the effects from HAV. In spite economic and cultural differences between different parts of the world, the vibrating tools function in the same way, exposing the workers to the same harm.

Impact wrenches are a much more common tool than rock drills and are used in all kinds of construction and mechanical industries. Impact wrenches does not expose the workers to the same levels of vibrations as the rock drills, but our studies shows that even moderate exposures to impact wrenches at vibration levels well below the present exposure action value may produce signs of reduced tactile perception associated with HAVS. A study by Bovenzi et al on HAV exposures from impact wrenches among work shop workers found an average daily exposure of 1.3 m/s^2 [106] which is very close to the exposure levels found in our study which was 1.2 m/s^2. These are quite low exposure levels, and below the exposure action value of 2.5 m/s^2. A study by Barregaard et al. among Swedish car mechanics also demonstrated similar findings [82], with an estimated daily exposure time of 14 minutes. In our study we estimated average exposure time of 15 minutes. Barregaard et al. found a prevalence of neurological symptoms of 25 % and 40 % after 12 and 20 years respectively. In a recent publication Gerhardsson et al. found a prevalence of neurosensory symptoms of 70% among male workers in a wheel loader assembly plant in Sweden with daily exposure to 2.2 m/s^2. Both authors argue that the high prevalence of symptoms among these workers who are exposed to relatively low levels of HAV exposure is caused by high frequency vibrations from impact wrenches. The weighting curve (Wh) of the ISO 5349-1 standard reduce the influence of the high frequencies and has a cut of at the octave band at 1250 Hz. This may underestimate the harmful effect from tools with high frequency contents, such as impact wrenches. Our studies also show signs among impact wrench users which could develop into neurological symptoms related to HAVS. However, we did not find similar strong effects as in the two afore mentioned studies. One reason for this could be that those studies were from indoor assembly plants were workers typically wear thin assembly gloves, or no gloves at all. The guard rail workers always wear thick heavy duty working gloves. In winter they wear gloves with insulation. These outdoor gloves will most likely absorb most of the energy from high frequency vibrations. Thus, the guard rail workers in our studies are perhaps not representative for workers who use impact wrenches indoors in assembly plants and similar workplaces.

Vibration meters with hand-attached accelerometers are commercially available and they are presented as a convenient alternative to the standardized measurement method which advice the use of tool-attached accelerometers. The five workers who participated in the measurement approach study (paper II) were a small sample out of the around 50 workers employed in the rock face stabilizing department. It is uncertain to what degree these workers are representative for the whole group of workers exposed to HAV from rock drills in the company, and thus for rock drill operators in general. However, the study revealed some important principles. Our measurements among rock drillers under realistic working conditions showed that there is potentially a high risk for bias in the measurements, both when using hand-attached accelerometers, and when using tool-attached accelerometers. The risk of this bias may go unnoticed if working technique of the workers are not studied thoroughly. This knowledge is relevant for most work were hand-guided rock drills are used, and plausibly also for other hand-guided tools where individual working techniques are observed.

10. MAIN CONCLUSIONS

Typical levels of exposure for road maintenance workers using rock drills as their main tool are 5.4 m/s^2 A8 of daily exposure, which is above the limit value (ELV) adopted by the EU, UK, US and many other countries in the world. Typical levels of exposure for road maintenance workers using impact wrenches as their main tool is 1.2 m/s^2 A8 of daily exposure, below the action value (EAV).

Our study supports earlier studies showing that workers using rock drills on a regular basis are at high risk for acquiring vibration related injuries. To our knowledge, this is the first study with a cohort design which shows an exposure response on an individual level between HAV exposure and neurological symptoms in the fingers, measured as vibration perception thresholds (VPT). We have shown that for every tenfold increase in lifetime cumulative exposure, up to 1.5 dB rise (worsening) could be explained by the HAV exposure. With lifetime exposures ranging up to 100 000 hours * m/s^2 in our study population, this means that a worsening of 7.5 dB could be explained by the exposure. It is more intuitive to understand the clinical significance of this if we show an example with VPT measured in m/s^2: If a worker has an increase in VPT of 6 dB, e.g. from 114 dB to 120 dB in a finger, then this is equivalent to a rise from 0.5 m/s^2 in VPT to 1 m/s^2 in VPT. According to UK diagnostic criteria, 0.7 m/s^2 is classified as a “possible disorder” and 1 m/s^2 as a “probable disorder” [100]. On a group level, the highest exposed workers were also those who reported most vascular and neurological symptoms, which further strengthens the clinical relevance of using VPT as a quantitative measure for health effect.

Measurement uncertainties related to the choice of accelerometer attachment have been given limited considerations in earlier studies. In our study we have identified individual working techniques and how they can cause bias in the exposure assessment and how such bias may be addressed.

We have also shown that relatively moderate exposures to impact wrenches as low as 1.2 m/s^2 A8 which is below the action value of 2.5 m/s^2 A8 may cause a worsened VPT. The implication of this finding is that companies with vibration exposed workers should try and reduce vibrations if possible and reasonable, also when exposures are below 2.5 m/s^2 A8.

Our findings suggests that screening workers by Vibrameter using the 500 Hz test frequency may possibly increase the sensitivity of the VPT method to identify early signs of reduced neurosensory function related to development of HAVS. However, more research is necessary before it is advisable to recommend this method for screening purposes.

Conclusions regarding research questions:

1. H_0: There is no exposure-response relationship between HAV exposure from rock drilling and VPT.
   H_1: There is an exposure-response relationship between HAV exposure from rock drilling and VPT.

   Conclusion: H_0 is rejected.

2. H_0: There is no exposure-response relationship between HAV exposure from impact wrench use and VPT.
   H_1: There is an exposure-response relationship between HAV exposure from impact wrench use and VPT.

   Conclusion: There are indications of a relationship, however not conclusive.

3. H_0: There is no exposure-response relationship between HAV exposure from rock drills and VPT on an individual level.
   H_1: There is an exposure-response relationship between HAV exposure from rock drills and VPT on an individual level.

   Conclusion: H_0 is rejected.

4. H_0: There is no exposure-response relationship between HAV exposure from impact wrench use and VPT on an individual level.
   H_1: There is an exposure-response relationship between HAV exposure from impact wrench use and VPT on an individual level.

   Conclusion: There are indications of a relationship, however not conclusive.

5. H_0: There is no systematic difference between measurement results obtained with hand-attached accelerometers compared to tool-attached accelerometers.
   H_1: There is a systematic difference between measurement result obtained with hand-attached accelerometers compared to tool-attached accelerometers.

   Conclusion: H_0 is rejected.

11. PRACTICAL IMPLICATIONS AND FUTURE PERSPECTIVES

In 2022 in the US, more than 800 000 were employed in the mining industry [107], which is a big market for handheld and hand-guided rock drills. ILO estimated in 1999 that there were 13 million people working in small-scale mining in the world, and the number was increasing massively in developing nations [108]. According to Annex C in ISO 5349-1 [69], if these workers have a moderate daily exposure of 2.5 m/s^2 A8 (EAV in the EU), 10 % are expected to suffer from vascular symptoms in the fingers after 12 years and if they have a high daily exposure of 5 m/s^2 A8 (ELV in the EU), 10 % are expected to suffer from vascular symptoms after just 6 years. According to the review by Nilsson et al [5], neurological symptoms can be expected even earlier. Thus, there are millions of people in the world today who are at risk to develop adverse health effects from HAV exposure from rock drills. Our studies show that both moderate and substantial use of the tools lead to exposure exceeding levels that are leading to changes in sensory nerve function in the hands and arms of the workers.

Therefore, it is a strong need to improve tools and reduce exposure levels using technical and organizational solutions in order to reduce risk of health damage due to exposure to hand-held and hand-guided vibrating tools.

Possibilities of better working techniques and modifications of auxiliary equipment, such as hand jacks and tool-handles should be adopted. Reduction of high-amplitude vibration using built-in mechanisms to reduce the transmission of tool vibrations to the hand and arm of the workers operating the tools are warranted.

There is also a need to improve measurement approaches when measuring HAV exposure from hand-guided tools such as rock drills, where contact between the vibrating tool, and the hands and fingers of the worker are intermittent and varies between workers. This is important because individual workers may be at high risk for adverse health effects not only based on the characteristics of the vibrating tool, but also based on individual characteristics in working technique. With the use of hand-attached accelerometers there is a risk of a bias towards too low measurement results, thus underestimating health risk. With the use of tool-attached accelerometers there is a risk of bias towards too high measurement results, thus overestimating health risk. If the generation of exposure-response models are based on epidemiological studies where exposure assessments have exaggerated exposure, then this may lead to an underestimating of the health risk because the health outcome in those studies are in fact caused by lower exposures.

This is important knowledge for the assessment of HAV related injuries in the future, both for employers monitoring vibration exposure in the workplace, and for researchers who are studying exposure-response models.

Further research on the 500 Hz test frequency as an early predictor of neurological damage is warranted, as well as research on how different vibration characteristics of handheld and hand-guided tools such as weight, frequency and impulsiveness, may affect risk for adverse health effects.

12. REFERENCES

1. Bovenzi, M., *Hand-arm vibration syndrome and dose-response relation for vibration induced white finger among quarry drillers and stonecarvers. Italian Study Group on Physical Hazards in the Stone Industry.* Occup Environ Med, 1994. **51**(9): p. 603-11.
2. Hoffman, L., *The Rock Drill and Civilization*. 1999, American Heritage Publishing: US.
3. Pelmear, P.L., *Epidemiology of Hand-Arm Vibration Syndrome*, in *Hand-Arm Vibration*, O. Press, Editor. 1998, OEM Health Information Inc: Beverly Farms, Massachusets, USA. p. 103-126.
4. Taylor, W., et al., *Effect of the air hammer on the hands of stonecutters. The limestone quarries of Bedford, Indiana, revisited.* Br J Ind Med, 1984. **41**(3): p. 289-95.
5. Nilsson, T., J. Wahlstrom, and L. Burstrom, *Hand-arm vibration and the risk of vascular and neurological diseases-A systematic review and meta-analysis.* PLoS One, 2017. **12**(7): p. e0180795.
6. Rytkonen, E., et al., *Hand-arm vibration exposure of dentists.* Int Arch Occup Environ Health, 2006. **79**(6): p. 521-7.
7. Vergara, M., et al., *Hand-transmitted vibration in power tools: accomplishment of standards and users' perception.* Industrial Ergonomics, 2007. **38**(9-10): p. 652-660.
8. Buhaug, K., B.E. Moen, and A. Irgens, *Upper limb disability in Norwegian workers with hand-arm vibration syndrome.* J Occup Med Toxicol, 2014. **9**(1): p. 5.
9. STAMI, N., LKU (Levekårsundersøkelsen 2019), *NOA / Norsk overvåkning av arbeidsmiljø*. 2020, STAMI: Oslo, Norway.
10. Wikipedia. *Vibration*. 2020 11 dec 2020 [cited 2021 13 jan]; Available from: https://en.wikipedia.org/wiki/Vibration.
11. Bovenzi, M., C.J. Lindsell, and M.J. Griffin, *Response of finger circulation to energy equivalent combinations of magnitude and duration of vibration.* Occup Environ Med, 2001. **58**(3): p. 185-93.
12. Starck, J., *High impulse acceleration levels in hand-held vibratory tools. An additional factor in the hazards associated with the hand-arm vibration syndrome.* Scand J Work Environ Health, 1984. **10**(3): p. 171-8.
13. Griffin, M.J., *Handbook of Human Vibration*. 1990, UK: Elsevier Academic Press. 988.
14. Welcome, D.E., et al., *An examination of the vibration transmissibility of the hand-arm system in three orthogonal directions.* Int J Ind Ergon, 2015. **45**: p. 21-34.
15. Pan, D., et al., *The relationships between hand coupling force and vibration biodynamic responses of the hand-arm system.* Ergonomics, 2017: p. 1-13.
16. Mansfield, N.J., *Human response to vibration*. 2005, USA: CRC Press. 227.
17. Aldien, Y., et al., *Mechanical impedance and absorbed power of hand-arm under x(h)-axis vibration and role of hand forces and posture.* Ind Health, 2005. **43**(3): p. 495-508.
18. Xu, X.S., et al., *Vibrations transmitted from human hands to upper arm, shoulder, back, neck, and head.* Int J Ind Ergon, 2017. **62**: p. 1-12.
19. Dart, E.E., *Effects of high speed vibrating tools on operators engaged in the airplane industry.* Occup Med (Chic Ill), 1946. **1**(6): p. 515-50.
20. Peters, F.M., *A disease resulting from the use of pneumatic tools.* Occup Med (Chic Ill), 1946. **2**: p. 55-66.
21. Agate, J.N. and H.A. Druett, *A study of portable vibrating tools in relation to the clinical effects which they produce.* Br J Ind Med, 1947. **4**(3): p. 141-63.
22. Virokannas, H., *Dose-response relation between exposure to two types of hand-arm vibration and sensorineural perception of vibration.* Occup Environ Med, 1995. **52**(5): p. 332-6.

23. Sauni, R., et al., *Dose-response relationship between exposure to hand-arm vibration and health effects among metalworkers.* Ann Occup Hyg, 2009. **53**(1): p. 55-62.
24. Taylor, W., *Vibration white finger: a newly prescribed disease.* Br Med J (Clin Res Ed), 1985. **291**(6500): p. 921-2.
25. Bovenzi, M., *Exposure-response relationship in the hand-arm vibration syndrome: an overview of current epidemiology research.* Int Arch Occup Environ Health, 1998. **71**(8): p. 509-19.
26. Griffin, M.J., M. Bovenzi, and C.M. Nelson, *Dose-response patterns for vibration-induced white finger.* Occup Environ Med, 2003. **60**(1): p. 16-26.
27. Herrick, A.L., *Pathogenesis of Raynaud's phenomenon.* Rheumatology (Oxford), 2005. **44**(5): p. 587-96.
28. Stoyneva, Z., *Postocclusive reactive hyperemia in hand-arm vibration syndrome.* Int J Occup Med Environ Health, 2016. **29**(4): p. 659-66.
29. Sakakibara, H., *Pathophysiology and Pathogenesis of Circulatory, Neurological, and Musculoskeletal Disturbances in Hand-Arm Vibration Syndrome*, in *Hand-Arm Vibration*, P.L. Pelmear and D.E. Wasserman, Editors. 1998, OEM PRESS. p. 45-63.
30. Rajagopalan, S., et al., *Increased asymmetric dimethylarginine and endothelin 1 levels in secondary Raynaud's phenomenon: implications for vascular dysfunction and progression of disease.* Arthritis Rheum, 2003. **48**(7): p. 1992-2000.
31. Palmer, K.T. and H. Mason, *Serum endothelin concentrations in workers exposed to vibration.* Occup Environ Med, 1996. **53**(2): p. 118-24.
32. Futatsuka, M. and Y. Fukuda. *A follow up study on the consequences of VWF patients in the workers using chain saws*. in *8th International Conference on Hand-Arm Vibration*. 1998. Umeå, Sweden.
33. Budd, D., D.L. Holness, and R. House, *Functional limitations in workers with hand-arm vibration syndrome (HAVS).* Occup Med (Lond), 2018.
34. Dahlin, L.B., et al., *Low myelinated nerve-fibre density may lead to symptoms associated with nerve entrapment in vibration-induced neuropathy.* J Occup Med Toxicol, 2014. **9**(1): p. 7.
35. Dahlin, L.B. and G. Lundborg, *Vibration-induced hand problems: role of the peripheral nerves in the pathophysiology.* Scand J Plast Reconstr Surg Hand Surg, 2001. **35**(3): p. 225-32.
36. Stromberg, T., et al., *Structural nerve changes at wrist level in workers exposed to vibration.* Occup Environ Med, 1997. **54**(5): p. 307-11.
37. Stromberg, T., et al., *Neurophysiological findings in vibration-exposed male workers.* J Hand Surg Br, 1999. **24**(2): p. 203-9.
38. Takeuchi, T., et al., *Pathological changes observed in the finger biopsy of patients with vibration-induced white finger.* Scand J Work Environ Health, 1986. **12**(4 Spec No): p. 280-3.
39. Lundborg, G., et al., *Intraneural edema following exposure to vibration.* Scand J Work Environ Health, 1987. **13**(4): p. 326-9.
40. Hjortsberg, U., et al., *Finger receptor dysfunction in dental technicians exposed to high-frequency vibration.* Scand J Work Environ Health, 1989. **15**(5): p. 339-44.
41. Chang, K.Y., S.T. Ho, and H.S. Yu, *Vibration induced neurophysiological and electron microscopical changes in rat peripheral nerves.* Occup Environ Med, 1994. **51**(2): p. 130-5.
42. Ho, S.T. and H.S. Yu, *Ultrastructural changes of the peripheral nerve induced by vibration: an experimental study.* Br J Ind Med, 1989. **46**(3): p. 157-64.
43. Takeuchi, T., M. Takeya, and H. Imanishi, *Ultrastructural changes in peripheral nerves of the fingers of three vibration-exposed persons with Raynaud's phenomenon.* Scand J Work Environ Health, 1988. **14**(1): p. 31-5.
44. Walton, K., *The pathology of Raynauds phenomenon of occupational origin*. The Vibration Syndrome, ed. W. Taylor. 1972, London: Academic Press.
45. Rosen, B., et al., *Cerebral changes after injury to the median nerve: a long-term follow up.* J Plast Surg Hand Surg, 2012. **46**(2): p. 106-12.

46. Lundstrom, R., et al., *Vibrotactile perception sensitivity and its relation to hand-arm vibration exposure.* Cent Eur J Public Health, 1995. **3 Suppl**: p. 62-5.
47. Lundstrom, R., et al., *Exposure-response relationship between hand-arm vibration and vibrotactile perception sensitivity.* Am J Ind Med, 1999. **35**(5): p. 456-64.
48. Malchaire, J., et al., *Bone and joint changes in the wrists and elbows and their association with hand and arm vibration exposure.* Ann Occup Hyg, 1986. **30**(4): p. 461-8.
49. Farkkila, M., et al., *Vibration-induced decrease in the muscle force in lumberjacks.* Eur J Appl Physiol Occup Physiol, 1980. **43**(1): p. 1-9.
50. Poole, C.J.M., et al., *International consensus criteria for diagnosing and staging hand-arm vibration syndrome.* Int Arch Occup Environ Health, 2018.
51. Roberts, H.C., et al., *A review of the measurement of grip strength in clinical and epidemiological studies: towards a standardised approach.* Age Ageing, 2011. **40**(4): p. 423-9.
52. Necking, L.E., J. Friden, and G. Lundborg, *Reduced muscle strength in abduction of the index finger: an important clinical sign in hand-arm vibration syndrome.* Scand J Plast Reconstr Surg Hand Surg, 2003. **37**(6): p. 365-70.
53. Lundborg, G., et al., *Digital vibrogram: a new diagnostic tool for sensory testing in compression neuropathy.* J Hand Surg Am, 1986. **11**(5): p. 693-9.
54. International_Organization_for_Standardization, *ISO 13091-1 Mechanical vibration -- Vibrotactile perception thresholds for the assessment of nerve dysfunction -- Part 1: Methods of measurement at the fingertips*. 2001.
55. Ruff, R.M. and S.B. Parker, *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**(3 Pt 2): p. 1219-30.
56. Amirjani, N., et al., *Validity and reliability of the Purdue Pegboard Test in carpal tunnel syndrome.* Muscle Nerve, 2011. **43**(2): p. 171-7.
57. Suda, M., et al., *Validity and Reliability of the Semmes-Weinstein Monofilament Test and the Thumb Localizing Test in Patients With Stroke.* Front Neurol, 2020. **11**: p. 625917.
58. International_Organization_for_Standardization, *ISO 14835-2:2005 - Cold provocation tests for the assessment of peripheral vascular function - Part 2: Measurement and evaluation of finger systolic blood pressure*. 2005.
59. Lindsell, C.J. and M.J. Griffin, *Standardized diagnostic methods for assessing components of the hand-arm vibration syndrome*. 1998, Health and Safety Executive: Sudbury, UK.
60. Harada, N., *Cold-stress tests involving finger skin temperature measurement for evaluation of vascular disorders in hand-arm vibration syndrome: review of the literature.* Int Arch Occup Environ Health, 2002. **75**(1-2): p. 14-9.
61. International_Organization_for_Standardization, *ISO 14835-1:2016 - Cold provocation tests for the assessment of peripheral vascular function - Part 1: Measurement and evaluation of finger skin temperature*. 2016.
62. Gemne, G., et al., *The Stockholm Workshop scale for the classification of cold-induced Raynaud's phenomenon in the hand-arm vibration syndrome (revision of the Taylor-Pelmear scale).* Scand J Work Environ Health, 1987. **13**(4): p. 275-8.
63. Brammer, A.J., W. Taylor, and G. Lundborg, *Sensorineural stages of the hand-arm vibration syndrome.* Scand J Work Environ Health, 1987. **13**(4): p. 279-83.
64. Gerhardsson, L., et al., *Vascular and nerve damage in workers exposed to vibrating tools. The importance of objective measurements of exposure time.* Appl Ergon, 2005. **36**(1): p. 55-60.
65. Palmer, K.T., et al., *Validity of self reported occupational exposures to hand transmitted and whole body vibration.* Occup Environ Med, 2000. **57**(4): p. 237-41.
66. Pelmear, P.L., *Raynaud's Phenomenon*, in *Hand-Arm Vibration*, P.L. Pelmear and D.E. Wasserman, Editors. 1998, OEM Press. p. 19-26.
67. Armstrong, T.J., et al., *Ergonomics and the effects of vibration in hand-intensive work.* Scand J Work Environ Health, 1987. **13**(4): p. 286-9.

68. Taylor, W., *The hand-arm vibration syndrome--diagnosis, assessment and objective tests: a review.* J R Soc Med, 1993. **86**(2): p. 101-3.

69. International_Organization_for_Standardization, *ISO 5349-1:2001 Mechanical vibration - Measurement and evaluation of human exposure to and-transmitted vibration - Part 1: General requirements* -. 2001, ISO: United Kingdom.

70. International_Organization_for_Standardization, *ISO 5349-2:2001 Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 2: Practical guidance for measurement at the workplace*. 2001.

71. Griffin, M.J., *Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration.* Occup Environ Med, 1997. **54**(2): p. 73-89.

72. Bovenzi, M., et al., *Frequency weightings of hand-transmitted vibration for predicting vibration-induced white finger.* Scand J Work Environ Health, 2011. **37**(3): p. 244-52.

73. Gerhardsson, L., et al., *Vibration-induced injuries in workers exposed to transient and high frequency vibrations.* J Occup Med Toxicol, 2020. **15**: p. 18.

74. Bovenzi, M., I. Pinto, and F. Picciolo, *Risk assessment of vascular disorders by a supplementary hand-arm vascular weighting of hand-transmitted vibration.* Int Arch Occup Environ Health, 2019. **92**(1): p. 129-139.

75. International_Organization_for_Standardization, *ISO 8041-2:2021 Human response to vibration -Measuring instrumentation- Part 2: Personal vibration exposure meters.* 2021.

76. Xu, X.S., et al., *An examination of the handheld adapter approach for measuring hand-transmitted vibration exposure.* Measurement (Mahwah N J), 2014. **47**: p. 64-77.

77. International_Organization_for_Standardization, *ISO 15230:2007 Mechanical vibration and shock - Coupling forces at the man-machine interface for hand-transmitted vibration*. 2007.

78. Bovenzi, M., et al., *Dose-response relation for vascular disorders induced by vibration in the fingers of forestry workers.* Occup Environ Med, 1995. **52**(11): p. 722-30.

79. Clemm, T., *Mekaniske vibrasjoner ved bruk av lufttrykksbor og risiko for hånd-arm vibrasjonssyndrom (mechanical vibrations while using rockdrills, and risk for hand-arm vibration syndrome)*. 2014, RVO - Arbeidstilsynet: Norway.

80. Brammer, A.J., *Dose-response relationships for hand-transmitted vibration.* Scand J Work Environ Health, 1986. **12**(4 Spec No): p. 284-8.

81. Niekerk, J.L.V., *Human vibration levels in the South African mining industry.* SAIMM Journal, 2000(July/August 2000): p. 235-242.

82. Barregard, L., L. Ehrenstrom, and K. Marcus, *Hand-arm vibration syndrome in Swedish car mechanics.* Occup Environ Med, 2003. **60**(4): p. 287-94.

83. Griffin, M.J. and M. Bovenzi, *VIBRISKS Final Technical Report, Protocol for epidemicological studies of hand-transmitted vibration, Annex 1, Appendix 8a*. 2007, University of Southampton UK, University of Trieste Italy.

84. 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: Practical guidance for measurement at the workplace*. 2001, ISO: United Kingdom.

85. Gerhardsson, L., L. Gillstrom, and M. Hagberg, *Test-retest reliability of neurophysiological tests of hand-arm vibration syndrome in vibration exposed workers and unexposed referents.* J Occup Med Toxicol, 2014. **9**(1): p. 38.

86. Ekman, L., et al., *Normative values of the vibration perception thresholds at finger pulps and metatarsal heads in healthy adults.* PLoS One, 2021. **16**(4): p. e0249461.

87. Rolke, R., et al., *Hand-arm vibration syndrome: clinical characteristics, conventional electrophysiology and quantitative sensory testing.* Clin Neurophysiol, 2013. **124**(8): p. 1680-8.

88. Krajnak, K., *Vibrotactile sensitivity testing for occupational and disease-induce peripheral neuropathies.* J Toxicol Environ Health B Crit Rev, 2021. **24**(4): p. 162-172.

89. Ellingsen, D.G., et al., *Hand tremor related to smoking habits and the consumption of caffeine in male industrial workers.* Neurotoxicology, 2006. **27**(4): p. 525-33.
90. Griffin, M., et al., *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. p. 35-36.
91. Ekman, L., J. Persson Lofgren, and L.B. Dahlin, *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**(12): p. e0226371.
92. Burstrom, L., et al., *Vibrotactile perception and effects of short-term exposure to hand-arm vibration.* Ann Occup Hyg, 2009. **53**(5): p. 539-47.
93. Malchaire, J., et al., *Neurological and functional effects of short-term exposure to hand-arm vibration.* Int Arch Occup Environ Health, 1998. **71**(4): p. 270-6.
94. Thonnard, J.L., et al., *Short-term effect of hand-arm vibration exposure on tactile sensitivity and manual skill.* Scand J Work Environ Health, 1997. **23**(3): p. 193-8.
95. International_Organization_for_Standardization, *ISO 8041-1:2017 Human response to vibration -Measuring instrumentation -Part 1: General purpose vibration meters.* 2017.
96. Wilson-MacDonald, J., M.A. Caughey, and D.B. Myers, *Diurnal variation in nerve conduction, hand volume, and grip strength in the carpal tunnel syndrome.* Br Med J (Clin Res Ed), 1984. **289**(6451): p. 1042.
97. Verrillo, R.T., *Effects of aging on the suprathreshold responses to vibration.* Percept Psychophys, 1982. **32**(1): p. 61-8.
98. Verrillo, R.T., S.J. Bolanowski, and G.A. Gescheider, *Effect of aging on the subjective magnitude of vibration.* Somatosens Mot Res, 2002. **19**(3): p. 238-44.
99. Lundstrom, R., T. Stromberg, and G. Lundborg, *Vibrotactile perception threshold measurements for diagnosis of sensory neuropathy. Description of a reference population.* Int Arch Occup Environ Health, 1992. **64**(3): p. 201-7.
100. Seah, S.A. and M.J. Griffin, *Normal values for thermotactile and vibrotactile thresholds in males and females.* Int Arch Occup Environ Health, 2008. **81**(5): p. 535-43.
101. Thomsen, N.O., et al., *Vibrotactile sense in patients with diabetes and carpal tunnel syndrome.* Diabet Med, 2011. **28**(11): p. 1401-6.
102. Hagberg, M., H. Morgenstern, and M. Kelsh, *Impact of occupations and job tasks on the prevalence of carpal tunnel syndrome.* Scand J Work Environ Health, 1992. **18**(6): p. 337-45.
103. Lawson, I.J., *Is carpal tunnel syndrome caused by work with vibrating tools?* Occup Med (Lond), 2020. **70**(1): p. 8-10.
104. Phillips, J.I., P.S. Heyns, and G. Nelson, *Rock drills used in South African mines: a comparative study of noise and vibration levels.* Ann Occup Hyg, 2007. **51**(3): p. 305-10.
105. Brubaker, R.L., C.J. Mackenzie, and S.G. Hutton, *Vibration-induced white finger among selected underground rock drillers in British Columbia.* Scand J Work Environ Health, 1986. **12**(4 Spec No): p. 296-300.
106. Bovenzi, M., et al., *Changes over a workshift in aesthesiometric and vibrotactile perception thresholds of workers exposed to intermittent hand transmitted vibration from impact wrenches.* Occup Environ Med, 1997. **54**(8): p. 577-87.
107. IBISWorld. *Mining in the US - Employment Statistics 2005-2028*. Industry Statistics - United States 2022 [cited 2022 18.11.2022]; Available from: https://www.ibisworld.com/industry-statistics/employment/mining-united-states/.
108. ILO. *Small-scale mining on the increase in developing countries*. 1999 [cited 2022 18.11.2022]; Available from: https://www.ilo.org/global/about-the-ilo/newsroom/news/WCMS_007929/lang--en/index.htm.
109. International_Organization_for_Standardization, *ISO/TR 18570:2017 Measurement an evaluation of human exposure to hand transmitted vibration – Supplementary method for assessing risk of vascular disorders.* 2017, ISO: United Kingdom

110. Taylor, M., et al., *An investigation of the Effects of Drill Operator Posture on Vibration Exposure and Temporary Threshold Shift of Vibrotactile Perception Threshold.* Vibration 2021. **4**(2): p. 395-405.

13. PUBLISHED PAPERS

Paper I: Dose–response relationship between hand–arm vibration exposure and vibrotactile thresholds among roadworkers

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

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

OPEN ACCESS

ORIGINAL RESEARCH

Dose–response relationship between hand–arm vibration exposure and vibrotactile thresholds among roadworkers

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ABSTRACT

Background Testing of vibration perception threshold (VPT) at the fingertips as a quantitative measure of tactile sensitivity is a commonly used tool in diagnosing hand–arm vibration syndrome. There is limited research on dose–response relationships between hand–arm vibration (HAV) exposure and VPT on an individual level.
Aims Assess possible dose–response relationships on an individual level between HAV exposure and VPT at the fingertips.
Methods We assessed average daily vibration exposure (m/s^{2}A8) and cumulative lifetime HAV exposure for 104 participants from different departments in a road maintenance company based on vibration measurements and questionnaires. VPT was measured based on the technical method described in ISO 13091-1:2005 using octave frequencies 8–500 Hz. We investigated associations using linear regression models with significance level $p \leq 0.05$.
Results The participants were either exposed to rock drills (n=33), impact wrenches (n=52) or none of these tools (n=19). Exposure to rock drills and impact wrenches was associated with elevated VPT for all seven test frequencies in the second and fifth fingers of both hands. A dose–response with the daily exposure measure m/s^2(A8) was found based on 1.2 m/s^2(A8) for impact wrenches, and 5.4 m/s^2(A8) for rock drills. A stronger association was found with the cumulative exposure for rock drills compared with impact wrenches, and for the second finger compared with the fifth finger.
Conclusions HAV exposure was associated with elevated VPT, also at exposure levels below the common exposure action value of 2.5 m/s^2(A8). Lowering the HAV exposure can contribute to prevent increasing VPTs in these workers.

Key messages

What is already known about this subject?

- Exposure to hand–arm vibration from vibrating tools can cause vascular and neurological signs and symptoms related to hand–arm vibration syndrome (HAVS).
- A dose–response relationship between exposure and vascular symptoms has been established in the research literature.

What are the new findings?

- A clear dose–response also for neurological signs related to HAVS, measured as vibration perception thresholds (VPT).
- Increased VPT was found also for workers exposed on regular basis to low levels of hand–arm vibration.

How might this impact on policy or clinical practice in the foreseeable future?

- There is a need to protect workers and monitor their exposure to hand–arm vibrations also at exposure levels below the common exposure action value of 2.5 m/s^2(A8) for daily exposure.
- Screening exposed workers for increased VPT may be used as a method to identify sensitive individuals in a workforce and to help decide whether further actions to reduce vibration exposure in a workforce are warranted.

INTRODUCTION

Hand–arm vibration (HAV) is a common work-related exposure. In a national survey in Norway, 42% of the construction workers reported exposures to HAV at work on a regular basis.[1]

Exposure to vibrating tools at work may lead to hand–arm vibration syndrome (HAVS).[2] The pathophysiological changes of HAVS include changes in the blood vessels, sensory corpuscles and nerves.[3 4] After years of exposure, this commonly leads to symptoms of white fingers, numbness, tingling and reduced sensory function. Subjective neurological symptoms such as numbness and tingling of the fingers are linked to increased vibration perception threshold (VPT) of the fingers.[5] These signs and symptoms may cause reduced hand performance.[6] The most relevant exposure metric of vibration exposure causing vascular and neurological changes has not yet been fully established. The exposure limit value (ELV) and exposure action value (EAV) for exposure to HAV are in most countries set at an acceleration level of respectively 5 m/s^2(A8) and 2.5 m/s^2(A8) as a time-weighted average for an 8-hour working day. The acceleration is calculated using root mean square averaging. The frequency weighting curve (W_h) defined in ISO 5349-1 is commonly used.[7] This standard refers to estimations of dose–response that predicts vibration white fingers (VWF) which is a diagnostic term describing the most typical vascular symptoms of HAVS. Dose–response relationships between exposure to vibration and outcomes have been established for the vascular component of HAVS.[8–10] For the neurological component of HAVS the results have been less clear. To assess tactile sensitivity, testing of VPT is commonly used as a quantitative measure. There are studies showing dose–response at a group level but not at an individual level between HAV exposure and VPTs.[11 12] Studies by Sauni *et al* and Virokannas were indicative of a dose–response relationship also at an individual level.[13 14] A cohort study by Bovenzi *et al* showed a dose–response for thermal sensation but not for VPT.[15] In that study, VPT was measured at two frequencies. There is currently no consensus regarding neither design of test equipment, nor which and how many frequencies should be included to test VPT.[16] Most of the literature investigating dose–response is based on exposure assessments on a group level with self-reported exposure time, likely to bias associations.[17 18]

The present study is a cross-sectional analysis of the inclusion phase of a prospective cohort study of symptoms and signs related to exposure to handheld vibrating tools among road-workers. In this study, we investigate the association between cumulative exposure to HAV and VPT. The aim of our study is to assess possible dose–response relationships between individual exposure to HAV from rock drills and impact wrenches and VPT tested at seven frequencies in the second and fifth fingers of both hands.

METHODS

Study design

A cross-sectional study design is used.

Inclusion of participants

We invited 108 workers employed in a Norwegian road maintenance company to participate in the study. The health examinations included a voluntary expansion of the ordinary health screening programme for the workers. All the rock face stabilisers and guardrail workers were invited to participate (n=60), because they were assumed to have the highest HAV exposure in the company. In addition, we invited workers (n=48) from other departments assumed to have no or low exposure to HAV. We did this to achieve an exposure contrast to the higher exposed workers. When investigating the exposure history of the participants in this group we discovered that many had similar exposures to impact wrenches or rock drills as the rock face stabilisers and guardrail workers, leaving only 19 workers unexposed to the two tools. Two workers among the rock face stabilisers refused to participate and one guardrail worker dropped out due to concurrent illness on the examination day. One participant among the unexposed did not show up for the scheduled appointment. The inclusion of subjects and baseline testing was performed during the period from November 2013 through March 2014.

Exposure assessment

We estimated vibration exposure based on field measurements done according to relevant parts of ISO 5349 part 1 and part 2.[7 19] The vibration metres Larson Davis HVM100 (Larson Davis, Depew, NY, USA) and Svantek SV106 (Svantek, Warszawa, Poland) were used for the measurements. Based on the measurements, we assigned the rock drillers an exposure to an average vibration magnitude of 17 m/s^2 during active operation of pneumatic rock drills, while the workers using battery-powered impact wrenches as their main tool were assigned an average exposure magnitude of 7 m/s^2. These levels correspond well to typical levels measured for these tools.[20] The average exposure time was estimated based on interviews with workers and time measurements in the field. A rock drill operator was exposed 47 min/workday on average, while an impact wrench operator was exposed for 15 min/workday on average. These exposures are equivalent to average daily exposure levels of 5.4 m/s^2(A8) for rock drill exposure and 1.2 m/s^2(A8) for impact wrench exposure.

To estimate lifetime cumulative exposure, information from questionnaires based on the VIBRISKS protocol (Risks of Occupational Vibration Exposures: Technical Report)[21] includes questions about exposure time per day, days per week, weeks per year and total years of exposure. Questions about the use of any vibrating tool other than the two main tools in the present and earlier occupational settings, as well as during leisure time were also included.

Vibrotactile perception thresholds

All the participants underwent a quantitative VPT test using VibroSense Meter (VibroSense Dynamics, Malmö, Sweden). The technical method was based on ISO 13091-1.[22] The second and fifth fingers on both hands were tested at seven frequencies: 8, 16, 32, 64, 125, 250 and 500 Hz, which include all the frequencies for VPT testing available with this instrument. The instrument uses the method of limits (often referred to as the von Bèkèsy method) with gradually increasing and decreasing sinusoidal vibration of a probe with a flat circular surface of 3 mm diameter.[23] The hand rests horizontally with the palm facing downwards. The finger to be tested rests with the pulp on the probe. A force indicator gives a light signal if the finger pressure is too high or too low to aid the patient in maintaining correct constant pressure during the test. The vibration magnitude of the probe increases in order of 3 dB/s, and the subjects press down a button with the opposite hand when they sense the vibrations and release the button when they no longer sense vibrations. This cycle is repeated and the vibration threshold for every frequency is calculated as the mean of four upper and lower limits of sensation. The test–retest reliability was found to be high in a study applying similar test equipment and methods.[24] The participants were not exposed to HAVs on the day of VPT testing.

Blood samples

Blood samples from the participants were analysed for parameters potentially relevant to the pathophysiology of reduced sensory nerve function. Whole blood was collected in parallel to VPT testing. Due to time constraints on the examination days, blood samples were obtained from only 93 participants. Analyses included haematology, glycated haemoglobin (HbA1c), C-reactive protein, carbohydrate-deficient transferrin (CDT), vitamin B_{12}, folate, albumin, alanine transaminase, glutamyl transpeptidase, cholesterol, caffeine, cotinine and thyroidal tests. All analyses were done by Fürst Medical Laboratory (Oslo, Norway). CDT was measured using capillary electrophoresis. A level of <1.7% was considered normal.[25] HbA1c levels were collected in EDTA tubes. Levels between 4.0% and 7.1% were considered normal. The method used for analysis of cotinine, caffeine and nicotine has been previously described in detail.[26] Information about body mass index (BMI) was collected in the questionnaires.

Statistical analysis

To investigate the associations between HAV and VPT we used multiple linear regression models in SPSS V.25 (IBM SPSS). In preparatory analysis, the potentially confounding factors BMI, cotinine, vitamin B$_{12}$, free T4, HbA1c and CDT were included in the regression models for all frequencies at the dominant second finger where the most significant associations were found. None of the information from the analyses of blood samples did confound the outcome. We classified age into intervals (20–29, 30–39, 40–49, 50–59 and 60–69). The age variable 60–69 was kept in the model as the analyses showed that only age at this level influenced the association, changing the estimate of effect with more than 10%. The number of hours multiplied with the typical acceleration level (hour·m/s^2) served as the main exposure measure for the operation of the two main tools. To investigate different outcomes based on which main tool the workers were exposed to, we split the independent exposure variable in two separate variables (rock drill exposure and impact wrench exposure). We also applied the acceleration level normalised to an 8-hour working day (m/s^{2}A8) multiplied by the number of days of operation for the two tools in models to investigate if the workers' exposure in relation to legislative EAV and ELV would provide any additional information. To enable log transformation, zero exposure to the main tools was substituted with hour·m/s^2=1. We log transformed the exposure measures to correct for skewness. Since the outcome is measured as threshold of perception measured in decibels, the models were built using a log-log transformed data set. Workers with injured or missing fingers were included in the analyses but only with the non-injured fingers.

RESULTS

Group characteristics

Of the 104 workers participating in the study, 33 were exposed to high acceleration levels from pneumatic rock drills, 52 were exposed to intermediate acceleration levels from battery-powered impact wrenches and the remaining 19 workers were unexposed to these tools, although some were exposed to ill-defined levels of exposure using different handheld tools (table 1).

Effects at the group level

On a group level, for all tested fingers and frequencies, the VPTs increased with exposure, and were highest among the rock drill operators. The impact wrench operators had higher VPT for all fingers and frequencies compared with those not exposed to any of the two main tools (table 2).

Effects at the individual level

We identified a statistically significant association with dose–response between increasing vibration exposure and elevated VPT for all seven frequencies on both the dominant second and fifth fingers, on the non-dominant second finger and five frequencies on the non-dominant fifth finger (table 3). Using different measures of the product of time and acceleration levels, a slightly higher explained variance was obtained in the models using acceleration (m/s^2) times the cumulative hours of lifetime exposure calculated as two independent variables; one for exposure to rock drills and one for exposure to impact wrenches (online supplementary table 6a,b) compared with the combined exposure for the two tools (table 3).

Table 1 Characteristics of the study population

	Type of exposure*		
	Rock drills (RD)	Impact wrenches (IW)	No exposure to RD or IW
n	33	52	19
Age (years), mean (SD)	40.1 (13.1)	42.7 (12.7)	33.7 (11.1)
Body mass index (kg/m^2), mean (SD)	26.1 (2.8)	28.8 (3.8)	28.3 (5.8)
Smoking or tobacco snuffing, n (%)	23 (70)	29 (56)	8 (42)
Cotinine (ng/mL), mean (SD)	446 (417)	331 (444)	177 (260)
CDT (%), mean (SD)	0.7 (0.5)	0.7 (0.2)	0.7 (0.1)
HbA1c, mean (SD)	5.3 (0.3)	5.2 (0.3)	5.3 (0.5)
Vibration exposure level (m/s^2)	17	7	NA†
Vibration exposure (min/day)	47	15	NA†
Vibration exposure (hour·m/s^2), mean (SD)	13 219 (25 144)	2209 (2631)	1†
Vibration exposure (years), mean (SD)	11.4 (11.6)	15.4 (13.8)	NA†
Finger/hand injuries (%)	6 (18)	7 (13)	3 (16)
Vibration white fingers (%)‡	6 (18)	0 (0)	0 (0)
Finger numbness (%)	12 (36)	7 (13)	5 (26)

*n=6 had been exposed both to rock drills and to impact wrenches. These individuals are included in the table as exposed to rock drills. Information on total years of vibration was missing for one worker in the other work group. Blood samples were missing for two rock drill operators, seven impact wrench operators and one in the no exposure group.

†No exposure to hand–arm vibration (HAV) or rare/occasional exposure from other tools than rock drills or impact wrenches. To enable log transformation, zero exposure to the main tools was substituted with hour·m/s^2=1.

‡Diagnosed by an occupational medical doctor.

CDT, carbohydrate-deficient transferrin; NA, not applicable.

Using the average daily exposure level (m/s^{2}A8) multiplied by lifetime exposure-days and including the exposure measure for rock drills (5.4 m/s^{2}A8) and impact wrenches (1.2 m/s^{2}A8) separately in models, then we found similar results for rock drills and somewhat weaker estimates of associations for impact wrenches, compared with lifetime hours times m/s^2. Based on exposure normalised to 8-hour daily exposure we identified an association in dominant second finger at all seven frequencies for rock drill operators and at four frequencies for impact wrench operators (table 4). Results from all four test fingers can be seen in online supplementary table 7a,b.

Variables based on information of self-reported lifetime use of other vibrating tools did not show any associations with the outcome (not shown). Among the covariates that were tested as potential confounders, ages 60–69 were shown to have an impact on the effect estimates, but none of the blood test results.

DISCUSSION

The average exposure to HAV among the rock drill operators exceeded the common ELV of 5 m/s^2(A8) for daily exposure. The impact wrench operators had low exposure to HAV; on average below both the common ELV and the EAV of 2.5 m/s^2(A8). Dose–response relationships between elevated VPTs at the second and fifth fingers of both hands and HAV exposure were shown. When splitting the cumulative exposure variable in two new variables based on tool exposure, the exposure measure for rock drills showed a stronger association with a clear dose–response relationship for both hands. The exposure measure for impact wrenches showed a weaker association, but still significant on some frequencies in the dominant hand.

For each added exposure unit of log acceleration·time (hour·m/s^2) the perception threshold was increased by 2.5 dB in the dominant second finger at the higher frequencies. The range of exposure was 1–100 000 hours·m/s^2 which equals 0–5 in the log-transformed variable. This means that a loss of VPT

Table 2 Vibrotactile perception thresholds, dB (SD) relative to 10^{-6} m/s^2, by frequency and finger

		Vibration perception thresholds, dB (SD)		
Test finger	Frequency (Hz)	Exposed to: rock drills n=33	Impact wrenches n=52	No exposure to RD/IW n=19
Dominant hand				
Second finger	8	104.0 (6.8)	101.4 (6.1)	98.1 (4.7)
	16	109.3 (6.0)	106.8 (5.3)	103.6 (4.1)
	32	113.2 (6.7)	110.9 (4.1)	108.7 (4.7)
	64	111.2 (8.8)	108.4 (6.4)	104.9 (6.5)
	125	110.1 (8.4)	106.4 (6.4)	103.3 (8.5)
	250	119.3 (9.8)	114.7 (8.1)	109.7 (9.8)
	500	132.9 (12.5)	126.4 (8.6)	123.1 (7.8)
Fifth finger*	8	104.0 (7.7)	100.6 (5.0)	97.9 (5.2)
	16	109.8 (7.0)	106.3 (4.9)	103.8 (5.9)
	32	113.2 (7.4)	110.9 (5.5)	108.4 (6.0)
	64	112.5 (9.3)	110.6 (6.9)	106.2 (5.9)
	125	112.6 (13.1)	108.3 (8.9)	103.5 (7.2)
	250	120.8 (15.8)	115.3 (11.8)	111.4 (9.9)
	500	132.4 (14.1)	128.5 (11.9)	122.6 (10.3)
Non-dominant hand				
Second finger†	8	102.2 (6.4)	99.2 (5.3)	98.5 (6.0)
	16	107.9 (6.7)	104.9 (6.1)	103.5 (5.6)
	32	111.3 (6.9)	109.6 (5.9)	106.9 (4.4)
	64	109.3 (8.1)	106.2 (7.6)	104.1 (7.0)
	125	109.3 (10.1)	105.6 (8.5)	102.7 (8.5)
	250	116.7 (12.3)	113.0 (10.1)	109.1 (10.0)
	500	128.6 (14.1)	124.5 (12.0)	119.7 (9.9)
Fifth finger‡	8	103.2 (7.3)	99.2 (5.4)	98.1 (3.6)
	16	108.2 (7.2)	105.3 (6.0)	103.7 (3.8)
	64	111.7 (10.2)	109.0 (7.4)	107.7 (6.3)
	125	111.5 (13.8)	107.4 (9.2)	105.6 (7.6)
	250	119.1 (14.8)	113.2 (10.9)	109.7 (9.2)
	500	130.5 (13.8)	126.5 (11.6)	121.9 (9.9)

*n=51 for impact wrench operators, n=18 for no exposure.
†n=50 for impact wrench operators.
‡n=51 for impact wrench operators.
IW, impact wrench; RD, rock drill.

Table 4 Association between HAV exposure to rock drills and impact wrenches as separate variables and VPTs on dominant second finger: elevated VPT (dB) per 10-fold increase in days exposed to daily vibration in m/s^2(A8)

Frequency	Rock drill exposure: 5.4 m/s^2(A8) Dominant second finger (n=104)	Impact wrench exposure: 1.2 m/s^2(A8) Dominant second finger (n=104)
Hz	Unstandardised coefficient B (95% CI)	Unstandardised coefficient B (95% CI)
8	2.08 (0.96 to 3.20)*	0.91 (–0.05 to 1.87)
16	1.96 (0.99 to 2.94)*	1.03 (0.20 to 1.87)*
32	1.86 (0.91 to 2.81)*	0.88 (0.07 to 1.69)*
64	2.23 (0.88 to 3.58)*	1.01 (–0.15 to 2.17)
125	2.65 (1.28 to 2.83)*	1.27 (0.10 to 2.44)*
250	3.40 (1.74 to 5.06)*	1.70 (0.28 to 3.12)*
500	3.36 (1.50 to 5.21)*	0.74 (–0.85 to 2.33)

Models included age (using categories of age <60 and ages 60–69 years), rock drill exposure and impact wrench exposure.
*P≤0.05.
HAV, hand–arm vibration; VPT, vibration perception threshold.

in the range of 0–12.5 dB could be explained by the exposure, meaning that the highest exposed workers showed a loss of 12.5 dB of the VPT compared with the lowest exposed. The clinical relevance of these numbers may be reflected by our study population where cases of VWF only were found among the highly exposed rock drillers, and the proportion of subjects reporting finger numbness was also highest in this group. For example, an elevation in VPT of 12 dB from 108 dB to 120 dB is equivalent to an elevation from 0.25 to 1 m/s^2. For the diagnosis of HAVS in the UK, VPTs are categorised into two: 'Possible disorder' and 'probable disorder'.[27] According to these criteria a VPT above 1 m/s^2 at the 125 Hz test frequency would be categorised as a probable disorder.

The stronger association between cumulative exposure from rock drills (m/s^2· hour) compared with exposure from impact wrenches could be explained by the much higher vibration magnitude of the rock drills. The characteristics of the rock drills that include peaks of high amplitudes could also be a contributing factor. A study comparing HAV from two different tools with different vibration characteristics (but same vibration magnitude in m/s^2) suggested that transient impulses can increase the risk of HAVS.[28]

It is possible that the weaker associations that we found for impact wrenches were caused by a possible baseline biological threshold where HAV exposure has no effect. Brammer[29] has proposed a baseline threshold of 1 m/s^2(A8) for vascular signs. This threshold could be similar for sensorineural signs. If exposure

Table 3 Association between HAV exposure and VPT: increase of VPT (dB) per 10-fold increase in exposure (hour·m/s^2)

Frequency	Dominant second finger (n=104)	Dominant fifth finger (n=102)	Non-dominant second finger (n=102)	Non-dominant fifth finger (n=103)
Hz	Unstandardised coefficient B (95% CI)	Unstandardised coefficient B (95% CI)	Unstandardised coefficient B (95% CI)	Unstandardised coefficient B (95% CI)
8	1.42 (0.57 to 2.27)*	1.47 (0.61 to 2.32)*	0.85 (0.02 to 1.67)*	0.97 (0.12 to 1.82)*
16	1.28 (0.53 to 2.03)*	1.40 (0.57 to 2.23)*	0.98 (0.08 to 1.87)*	0.94 (0.06 to 1.81)*
32	1.11 (0.37 to 1.84)*	1.14 (0.27 to 2.01)*	0.99 (0.14 to 1.84)*	0.53 (–0.40 to 1.46)
64	1.52 (0.50 to 2.55)*	1.83 (0.78 to 2.88)*	1.38 (0.31 to 2.45)*	1.10 (–0.06 to 2.26)
125	1.64 (0.59 to 2.69)*	2.16 (0.72 to 3.59)*	1.63 (0.35 to 2.91)*	1.59 (0.08 to 3.09)*
250	2.40 (1.09 to 3.61)*	2.39 (0.57 to 4.21)*	1.99 (0.46 to 3.51)*	2.26 (0.56 to 3.96)*
500	1.99 (0.56 to 3.43)*	2.76 (1.03 to 4.48)*	2.16 (0.42 to 3.90)*	2.07 (0.36 to 3.77)*

All associations were age adjusted, using categories of age <60 and ages 60–69 years.
*P≤0.05.
HAV, hand–arm vibration; VPT, vibration perception threshold.

below 1 m/s^2(A8) has too little energy to cause physical harm in human tissue, only a small percentage of the HAV exposure from using the impact wrenches (1.2 m/s^{2}A8) would be harmful compared with exposure from the rock drills (5.4 m/s^{2}A8).

The weaker associations between impact wrenches and VPTs of the non-dominant hands are also likely to be influenced by the fact that the battery-powered impact wrenches in use were tools operated by one hand, as opposed to the pneumatic rock drills normally operated using both hands.

A limitation of our study is the uncertainty regarding the lifetime exposure to HAV for some of the workers. We put much effort in the exposure assessment. However, it is challenging to achieve accurate lifetime exposure for HAV-exposed workers because there are many variables that are difficult to evaluate in retrospect, the most important being exposure time and vibration levels for the vibrating tools that participants in the study reported to be exposed to in the past. Variability of exposure resulting from effects of lack of maintenance of tools being used, external conditions such as hardness of the rock being drilled and individual working techniques are also sources of uncertainty. Such variability will most likely result in non-differential misclassification of the exposure, leading to diluted estimates of association.

Because this a cross-sectional study, we cannot conclude about causality between exposure and effect, even though there seems to be a strong relationship. Selection bias such as the healthy worker effect may be present. Acute symptoms such as numbness and tingling after vibration exposures of high magnitudes can be experienced among workers,[30] and it may be that workers finding these symptoms uncomfortable are more prone to change jobs. If these are the workers most susceptible to increased VPTs it might cover up an even stronger association. Chronic symptoms related to HAVS may also cause workers to change jobs.

Age confounded the association between exposure and VPT, but only among the participants aged 60–69 years. Many studies report an association between age and VPTs.[31–33] However, a study by Seah and Griffin did not find this association.[27] It is possible that a healthy worker effect in our study has concealed a stronger association with age.

Different methods of assessing vibrotactile thresholds have been published and these methods do not directly compare because of differences of the test equipment such as the size of the vibrating probe, the use of surround (supportive surface around the probe) and the use of automatic control of finger force against probe.[16] There are published reference values for VPTs based on testing equipment that resembles the one used in our study,[33 34] but not on identical equipment. However, because our study assessed workers with a variation of exposure to HAV, the results for the workers not having rock drills or impact wrenches as their main tool could be considered as reference levels. A strength of using this reference group is that they have a similar level of education and income. They are therefore likely to be of comparable socioeconomic background.

A recent proposal for consensus about diagnosing HAVS mentions two frequencies for assessing vibrotactile thresholds: 31.5 Hz and 125 Hz.[35] This is in agreement with proposed testing frequencies in ISO 13091-1.[22] However, there is limited research about the relevance of testing frequencies higher than 125 Hz.[15] A study by Rolke *et al*[36] showed that thresholds around 125 Hz were most sensitive to cumulative vibration exposure. Our study suggests that the greatest threshold elevations are identified at 250 and 500 Hz, and in most cases, the associations with exposure were also strongest at these frequencies. It could be hypothesised that an early prediction of harmful effects from HAV exposure can be found when assessing these higher frequencies. However, when looking at the VPTs for the workers exposed to impact wrenches it is difficult to conclude because it seems random which frequencies show statistically significant associations. It is possible that the different characteristics of HAV not accounted for by exposure measurement (such as frequency and impulsiveness) may cause different frequency patterns in the vibrograms of HAV-exposed workers. That could be an argument to include a wider range of frequencies for VPT testing. More research on the characteristics of HAV exposure and its possible influence on VPTs at different frequencies could be useful for early diagnosis or predictions about HAVS.

It is not surprising that the high exposure from rock drills causes elevated VPTs. It is however interesting that there is a significant association on some frequencies also for the much lower exposed impact wrench operators. Based on the exposure measurements and time measurements, the average time-weighted daily exposure is 1.2 m/s^2(A8) for the workers exposed to impact wrenches. The study by Sauni *et al*[13] also found a dose–response relationship between a relatively low daily HAV exposure of 1.6 m/s^2(A8) and VPTs in metal workers using impact wrenches.

We used the W_h weighting curve described in the ISO 5349 standards[7 19] for our exposure measurements. It has been proposed that frequency weightings with more weight on higher frequency spectra would be more appropriate for predicting vascular symptoms.[37] However, for predicting sensorineural changes such as higher VPT the W_h has been evaluated and found appropriate for vibrating tools with low vibration frequencies,[38] such as rock drills and impact wrenches.

Our validation of the workers' self-reported exposure time (by doing time measurements) resulted in a much lower exposure time as compared with the self-reports. This difference must be considered when comparing our results to studies only relying on self-reported daily exposure time. Workers' tendency to report too long exposure times is well known.[17–19]

The present study demonstrates the need to reduce workers' HAV exposure even at levels below the EAV of 2.5 m/s^2(A8). Elevated VPTs have been shown to be associated with patients' complaints of numbness and white fingers[30 37] and the elevated VPTs among the workers exposed to these relatively low exposure levels could be a sign of early stages of an occupational disease.

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REFERENCES

1. Tynes T, Sterud T, Løvseth E, *et al*. *Faktabok Om arbeidsmiljø OG helse 2018*. Norway: The National Institute of Occupational Health, 2018.
2. Pelmear PL. The clinical assessment of hand-arm vibration syndrome. *Occup Med* 2003;53:337–41.
3. Herrick AL. Pathogenesis of Raynaud's phenomenon. *Rheumatology* 2005;44:587–96.
4. Dahlin LB, Sandén H, Dahlin E, *et al*. Low myelinated nerve-fibre density may lead to symptoms associated with nerve entrapment in vibration-induced neuropathy. *J Occup Med Toxicol* 2014;9:7.
5. Ye Y, Griffin MJ. Assessment of thermotactile and vibrotactile thresholds for detecting sensorineural components of the hand-arm vibration syndrome (HAVS). *Int Arch Occup Environ Health* 2018;91:35–45.
6. Sakakibara H, Hirata M, Toibana N. Impaired manual dexterity and neuromuscular dysfunction in patients with hand-arm vibration syndrome. *Ind Health* 2005;43:542–7.
7. International Organization for Standardization. *ISO 5349-1:2001 Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 1: General requirements*, 2001.
8. Griffin MJ, Bovenzi M, Nelson CM. Dose-response patterns for vibration-induced white finger. *Occup Environ Med* 2003;60:16–26.
9. Bovenzi M. Hand-Arm vibration syndrome and dose-response relation for vibration induced white finger among quarry drillers and stonecarvers. Italian Study Group on physical hazards in the stone industry. *Occup Environ Med* 1994;51:603–11.
10. Bovenzi M, Franzinelli A, Mancini R, *et al*. Dose-response relation for vascular disorders induced by vibration in the fingers of forestry workers. *Occup Environ Med* 1995;52:722–30.
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. 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.
14. 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.
15. Bovenzi M, Ronchese F, Mauro M. A longitudinal study of peripheral sensory function in vibration-exposed workers. *Int Arch Occup Environ Health* 2011;84:325–34.
16. Gandhi MS, Sesek R, Tuckett R, *et al*. Progress in vibrotactile threshold evaluation techniques: a review. *J Hand Ther* 2011;24:240–56. quiz 56.
17. 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.
18. 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.
19. International Organization for Standardization. *ISO 5349-2:2001 Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 2: Practical guidance for measurement at the workplace*, 2001.
20. Griffin M, Pitts PM, Kaulbars U. *Guide to good practice on Hand-arm Vibration. European Commission, Quality of Life and Management of Living resources Programme Key action 4 - Environment and Health*, 2007.
21. Griffin MJ, Bovenzi M. *VIBRISKS final technical report, protocol for epidemiological studies of hand-transmitted vibration, Annex 1, appendix 8a*. University of Southampton UK, University of Trieste Italy, 2007.
22. International Organization for Standardization. *ISO 13091-1 Mechanical vibration - Vibrotactile perception thresholds for the assessment of nerve dysfunction - Part 1: Methods of measurement at the fingertips*, 2001.
23. 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.
24. 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.
25. Ellingsen DG, Kusraeva Z, Bast-Pettersen R, *et al*. The interaction between manganese exposure and alcohol on neurobehavioral outcomes in welders. *Neurotoxicol Teratol* 2014;41:8–15.
26. 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.
27. Seah SA, Griffin MJ. Normal values for thermotactile and vibrotactile thresholds in males and females. *Int Arch Occup Environ Health* 2008;81:535–43.
28. Starck J, Pyykkö I. Impulsiveness of vibration as an additional factor in the hazards associated with hand-arm vibration. *Scand J Work Environ Health* 1986;12:323–6.
29. Brammer AJ. Threshold limit for hand-arm vibration exposure throughout the workday. In: Brammer AJ, taylor D, eds. *Vibration effects on the hand and arm in industry*. New York: John Wiley, 1982: 376.
30. Malchaire J, Rodriguez Diaz LS, Piette A, *et al*. Neurological and functional effects of short-term exposure to hand-arm vibration. *Int Arch Occup Environ Health* 1998;71:270–6.
31. Verrillo RT, Bolanowski SJ, Gescheider GA. Effect of aging on the subjective magnitude of vibration. *Somatosens Mot Res* 2002;19:238–44.
32. Verrillo RT. Effects of aging on the suprathreshold responses to vibration. *Percept Psychophys* 1982;32:61–8.
33. Lundström R, Strömberg T, Lundborg G. Vibrotactile perception threshold measurements for diagnosis of sensory neuropathy. description of a reference population. *Int Arch Occup Environ Health* 1992;64:201–7.
34. Ahn R, Yoo C-I, Lee H, *et al*. Normative data for neuromuscular assessment of the hand-arm vibration syndrome and its retrospective applications in Korean male workers. *Int Arch Occup Environ Health* 2013;86:837–44.
35. 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.
36. 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.
37. Bovenzi M, Pinto I, Picciolo F, *et al*. Frequency weightings of hand-transmitted vibration for predicting vibration-induced white finger. *Scand J Work Environ Health* 2011;37:244–52.
38. Pitts PM, Mason HJ, Poole KA, *et al*. Relative Performance of Frequency Weighting W(h) and Candidates for Alternative Frequency Weightings for Predicting the Occurrence of Hand-transmitted Vibration-induced Injuries. *Ind Health* 2012;50:388–96.

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Original Article

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 handgrips 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; Pelmear, 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	1.26
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	−2.84
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	−11.7
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	−7.31
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	−9.61
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				

[a] Model 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

[a] Model 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 ($\mathrm{m\ s^{-2}}$ RMS)	Range ($\mathrm{m\ s^{-2}}$ 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

[a] The 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 $\mathrm{m\ s^{-2}}$. The mean vibration magnitude measured on the tool was 28.5 $\mathrm{m\ s^{-2}}$ and measured in the hand, 19 $\mathrm{m\ s^{-2}}$. Calculated as percentages of the mechanical energy ($[\mathrm{m\ s^{-2}}]^2$), 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 $\mathrm{m\ s^{-2}}$. 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.

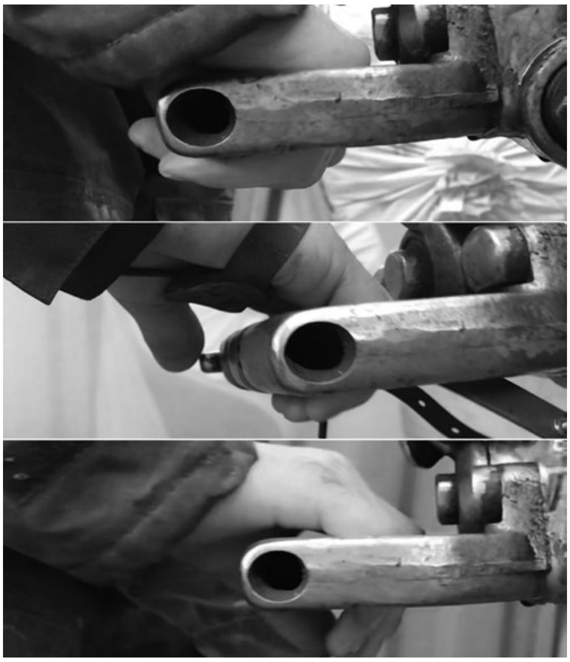

Figure 2. Type 1–3 hand grips (from top to bottom respectively). Top: closed grip with fingers and palm flexed around tool handle. Middle: semi-open grip with only fingers flexed around tool handle (no contact between tool handle and accelerometer). Bottom: open grip.

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 m s^{-2} 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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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, Hambert 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.

III

OPEN ACCESS

Original research

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

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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 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 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.

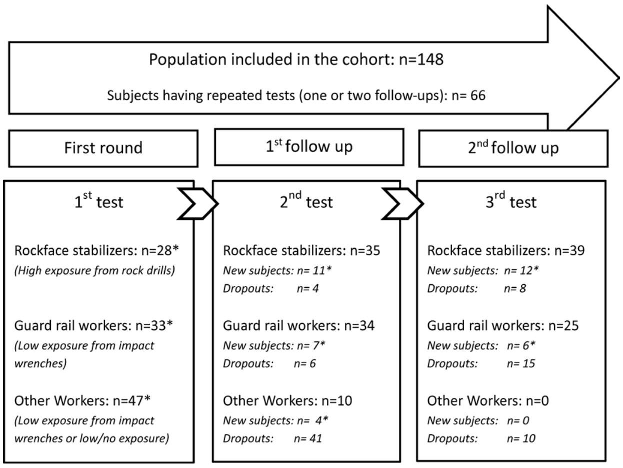

Figure 1 Participation data at baseline and at follow-up tests in the cohort . *Baseline individual test.

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≤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 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]

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.

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 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.

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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.

14. APPENDIX 1: Questionnaire

Intervjuskjema Prosjekt - Eksponering for vibrasjoner fra håndholdt verktøy og risiko for utvikling av hånd-arm-vibrasjonssyndrom (HAVS)

Seksjon 1 – Person identifikasjon

Mobil tlf:_______________

ID nummer ________ Fødselsdato: ____________ Dato

Seksjon 2 – Arbeidshistorie

2.1 Nåværende arbeid:

2.1.1 Yrkestittel__________________________

2.1.2 Arbeidsområde Fjellsikring Nei __ Ja __

Rekkverksarbeider Nei __ Ja __

Veiarbeider/fagarbeider (kontrollgruppe) Nei __ Ja __

2.1.3 Når startet du i Mesta? _________ (årstall)

2.1.4 Bruker du håndholdte vibrerende verktøy i nåværende arbeid? Nei __ Ja __

Hvis nei, gå til spm. 2.2

2.1.5 Hvis ja, hva slags verktøy bruker du?

Spørsmål spesielt for fjellsikrere:

	Varighet			
Verktøy brukt	Antall år	Uker pr år	Dager pr uke	Antall borehull pr dag
Fjellborr				

Spørsmål spesielt for rekkverksarbeidere:

	Varighet			
Verktøy brukt	Antall år	Uker pr år	Dager pr uke	Antall meter rekkverk pr dag
Muttertrekker				

Andre vibrerende verktøy fylles ut i neste tabell:

Spørsmål for ALLE arbeidsområder:

	Varigheten verktøyet er i bruk hvor hendene er i kontakt med vibrasjoner. Forklar siste kolonne for arbeidstakeren med: “Hvor mange minutter rister det i løpet av dagen?”			
Hvilke vibrerende verktøy brukt?	Antall år	Uker pr år	Dager pr uke	Minutter pr dag

2.1.6 Hvor mange dager eller timer er det siden du arbeidet sist med vibrerende verktøy

:____ (mer enn en uke er irrelevant).

2.1.7 Bruker du vibrasjonsdempende hansker? Nei __ Ja __

*2.2 **ALLE:** Har du i tidligere arbeidsforhold arbeidet med håndholdte vibrerende verktøy?* Nei __ Ja __

	Varigheten verktøyet er i bruk hvor hendene er i kontakt med vibrasjoner. "Hvor mange minutter rister det i løpet av dagen?"			
Hvilke vibrerende verktøy brukt?	Antall år	Uker pr år	Dager pr uke	Minutter pr dag

Beskrivelse av arbeid med tidligere eksponering for vibrasjoner fra håndholdte verktøy:

____

____

2.3 Når startet din første eksponering for håndholdte vibrerende verktøy? ______ (årstall)

2.4 Har du noen gang brukt håndholdte vibrerende verktøy regelmessig i fritiden? Nei __ Ja __

	Varigheten verktøyet er i bruk hvor hendene er i kontakt med vibrasjoner. "Hvor mange minutter rister det i løpet av dagen?"			
Verktøy brukt (hvilke?)	Antall år	Uker pr år	Dager pr uke	Minutter pr dag

Seksjon 3 – Sosial historie

3.1 Nikotinbruk

Røyker du? Nei __ Ja __

Har du røykt tidligere? Nei __ Ja __

Snuser du? Nei __ Ja __

Seksjon 4 – Medisinsk historie

4.1 Har du oppsøkt lege for, eller har du hatt noen av disse sykdommene/plagene?

		Evt. diagnostisert i hvilket år?
a. Diabetes /sukkersyke	Nei __ Ja __	______________________
b. Høyt blodtrykk	Nei __ Ja __	_______________________
c. Hjertesykdom	Nei __ Ja __	_______________________
d. Ledd eller muskelsykdom	Nei __ Ja __	_______________________

e. Arm- eller håndleddsbrudd Nei __ Ja __ ______________________

f. Migrene Nei __ Ja __ ______________________

g. Hvite fingre Nei __ Ja __ ______________________

h. Nervesykdom (for eksempel karpalt tunnelsyndrom) Nei __ Ja __ Hvilken _______________

i. Forfrysninger i hendene Nei __ Ja __ ______________________

j. Andre sykdommer Nei __ Ja __

Hvilke?____

4.2 Er det noen i din familie som er plaget med hvite fingre? Nei __ Ja __

Hvis ja, hva slags yrke har dette familiemedlemmet? _________________________________

4.3 Tar du følgende medikamenter regelmessig?

a. Migrenemedisin Nei __ Ja __ Hvilken type?_________________

b. Hjerte- eller blodtrykksmedisin Nei __ Ja __ Hvilken type?_________________

c. Annen medisin Nei __ Ja __ Hvilken type?_________________

Seksjon 5 – Symptomer

5.1. Fargeforandringer

5.1.1 Har du noen gang opplevd hvite fingre? Nei __ Ja __

Hvis nei, gå til 5.2

5.1.2 Hvis ja, når opplevde du dette første gang? __________(årstall)

5.1.3 Når var siste gang du opplevde dette? __ dager siden ___ måneder siden ___ år siden

5.1.4 Hvis du lider av hvite fingre, hvor ofte skjer dette?

Flere ganger i året Nei __ Ja __

Flere ganger i måneden Nei __ Ja __

Flere ganger i uka Nei __ Ja __

Flere ganger om dagen Nei __ Ja __

5.1.5 Opptrer disse på vinteren, sommeren eller begge?

Vinter Nei __ Ja __

Sommer Nei __ Ja __

Begge Nei __ Ja __

5.1.6 Hvor mange anfall med hvite fingre hadde du den forrige vinteren? (angi i tabellen nedenfor)

0	1-10	11-30	30-100	> 100

5.1.7 Hvor mange anfall med hvite fingre hadde du den forrige sommeren? (angi i tabellen nedenfor)

0	1-5	6-10	10-19	> 20

5.1.8 Noen faktorer som utløser det?

Kulde   Nei __ Ja __

Håndtere kalde gjenstander Nei __ Ja __

Når du kjenner vibrasjoner fra vibrerende verktøy   Nei __ Ja __

Andre faktorer Nei __ Ja __ Hvilke? ____

5.2. Prikking

5.2.1 Har du noen gang opplevd prikking i fingrene?   Nei __ Ja __

Hvis *nei*, gå til 5.3

5.2.2 Hvis ja, når opplevde du dette første gang?   __________(årstall)

5.2.3 Når opplevde du prikking?

Konstant Nei __ Ja __

Mens du arbeidet med vibrerende verktøy Nei __ Ja __

Etter eksponering for kulde Nei __ Ja __

Samtidig med hvite fingre Nei __ Ja __

Etter hvite fingre Nei __ Ja __

Om natten Nei __ Ja __

Til andre tider Nei __ Ja __ Når? ________________

5.3. Nummenhet

5.3.1 Blir fingrene dine numne? Nei __ Ja __

Hvis *nei*, gå til 5.4

5.3.2 Hvis ja, når opplevde du dette første gang? __________(årstall)

5.3.3 Når opplevde du nummenhet?

Konstant Nei __ Ja __

Mens du arbeidet med vibrerende verktøy Nei __ Ja __

Etter å ha arbeidet med vibrerende verktøy Nei __ Ja __

Etter eksponering for kulde Nei __ Ja __

Samtidig med hvite fingre Nei __ Ja __

Etter hvite fingre Nei __ Ja __

Om natten Nei __ Ja __

Til andre tider Nei __ Ja __ Når? ________________________

5.4 Kalde hender

Lider du ofte av kalde hender mer enn andre gjør ved tilsvarende aktivitet? Nei __ Ja __

5.5 Håndfunksjon

Har du noe av følgende?	Nei	Ja
Lett for å miste gjenstander	☐	☐
Vansker med å kneppe knapper	☐	☐
Vansker med å åpne et tettsittende lokk	☐	☐
Vansker med å håndtere og/eller plukke opp mynter	☐	☐
Vansker med å helle fra vannmugge eller kaffekanne	☐	☐
Vansker med å vri om et dørhåndtak	☐	☐
Vansker med å ta på jakke eller genser	☐	☐

15. APPENDIX 2: Supplemental materials

15.1 Paper I: Dose–response relationship between hand–arm vibration exposure and vibrotactile thresholds among roadworkers

Table 6 a. Association between HAV exposure to rock drills and impact wrenches as separate variables and VPT on dominant hand: Elevated VPT (dB) per tenfold increase in h · ms^{-2}

Frequency	Rock drill exposure Dominant 2nd finger (n=104)	Impact wrench exposure Dominant 2nd finger (n=104)	Rock drill exposure Dominant 5th finger (n=102)	Impact wrench exposure Dominant 5th finger (n=102)
Hz	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)
8	1.43 (0.64 - 2.23)*	0.84 (-0.06 - 1.73)	1.63 (0.84 - 2.43)*	0.76 (-0.12 - 1.65)
16	1.38 (0.69 - 2.07)*	0.97 (0.19 - 1.75)*	1.56 (0.79 - 2.33)*	0.67 (-0.19 - 1.53)
32	1.28 (0.60 - 1.96)*	0.82 (0.06 - 1.58)*	1.25 (0.44 - 2.07)*	0.74 (-0.17 - 1.66)
64	1.55 (0.58 - 2.51)*	0.93 (-0.15 - 2.02)	1.68 (0.68 - 2.68)*	1.30 (0.19 - 2.42)*
125	1.86 (0.89 - 2.83)*	1.19 (0.09 - 2.28)*	2.19 (0.84 - 3.55)*	1.11 (-0.41 - 3.55)
250	2.40 (1.22 - 3.58)*	1.58 (0.25 - 2.90)*	2.48 (0.77 - 4.20)*	1.05 (-0.87 - 2.97)
500	2.38 (1.07 - 3.70)*	0.72 (-0.76 - 2.19)	2.56 (0.92 - 4.20)*	2.04 (0.21 - 3.86)*

* $P \leq 0.05$

Models included age (using categories of age <60 and age 60-69 years), rockdrill exposure and impact wrench exposure

Table 6 b. Association between HAV exposure to rock drills and impact wrenches as separate variables and VPT on non-dominant hand: Elevated VPT (dB) per tenfold increase in $h \cdot ms^{-2}$

Frequency	Rock drill exposure Non-dominant 2nd finger (n=102)	Impact wrench exposure Non-dominant 2nd finger (n=102)	Rock drill exposure Non-dominant 5th finger (n=103)	Impact wrench exposure Non-dominant 5th finger (n=103)
Hz	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)
8	0.96 (0.19 - 1.72)*	0.16 (-0.72 - 1.03)	1.33 (0.56 - 2.10)*	0.36 (-0.51 - 1.23)
16	1.06 (0.23 - 1.89)*	0.38 (-0.57 - 1.32)	1.13 (0.32 - 1.94)*	0.50 (-0.42 - 1.42)
32	0.89 (0.08 - 1.69)*	0.58 (-0.33 - 1.49)	0.79 (-0.08 - 1.66)	0.18 (-0.80 - 1.16)
64	1.43 (0.43 - 2.43)*	0.75 (-0.39 - 1.89)	1.14 (0.05 - 2.23)*	0.32 (-0.92 - 1.55)
125	1.77 (0.58 - 2.96)*	0.99 (-0.37 - 2.34)	1.63 (0.23 - 3.04)*	0.35 (-1.24 - 1.94)
250	1.98 (0.55 - 3.41)*	1.21 (-0.42 - 2.83)	2.37 (0.79 - 3.96)*	0.81 (-0.98 - 2.60)
500	2.15 (0.52 - 3.78)*	1.33 (-0.52 - 3.19)	1.95 (0.34 - 3.56)*	0.98 (-0.83 - 2.80)

* $P \leq 0.05$

Models included age (using categories of age <60 and age 60-69 years), rock drill exposure and impact wrench exposure

Table 7 a. Association between HAV exposure to rock drills and VPT: Elevated VPT (dB) per tenfold increase in days exposed to 5.4 ms^{-2}(A8) for all tested fingers

Frequency	Dominant 2nd finger (n=104)	Dominant 5th finger (n=102)	Non-dominant 2nd finger (n=102)	Non-dominant 5th finger (n=103)
Hz	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)
8	2.08 (0.96 - 3.20)*	2.42 (1.31 - 3.53)*	1.37 (0.30 - 2.45)*	1.84 (0.75 - 2.93)*
16	1.96 (0.99 - 2.94)*	2.28 (1.20 - 3.35)*	1.48 (0.30 - 2.65)*	1.59 (0.45 - 2.73)*
32	1.86 (0.91 - 2.81)*	1.85 (0.70 - 3.00) *	1.22 (0.08 - 2.35)*	1.11 (-0.11 - 2.33)
64	2.23 (0.88 - 3.58)*	2.53 (1.13 - 3.93)*	2.12 (0.71 - 3.52)*	1.77 (0.24 - 3.30)*
125	2.65 (1.28 - 2.83)*	3.21 (1.31 - 5.12)*	2.56 (0.89 - 4.24)*	2.51 (0.54 - 4.49)*
250	3.40 (1.74 - 5.06)*	3.70 (1.29 - 6.11)*	2.88 (0.87 - 4.90)*	3.50 (1.27 - 5.72)*
500	3.36 (1.50 - 5.21)*	3.72 (1.42 - 6.02)*	3.10 (0.81 - 5.40)*	2.83 (0.56 - 5.09)*

* $P \leq 0.05$

Models included age (using categories of age <60 and age 60-69 years), rock drill exposure and impact wrench exposure

Table 7 b. Association between HAV exposure to impact wrenches and VPT: Elevated VPT (dB) per tenfold increase in days exposed to 1.2 ms^{-2}(A8) for all tested

Frequency	Dominant 2nd finger (n=104)	Dominant 5th finger (n=102)	Non-dominant 2nd finger (n=102)	Non-dominant 5th finger (n=103)
Hz	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)	Unstandardized Coefficients B (95 % CI)
8	0.91 (-0.05 - 1.87)	0.85 (-0.09 - 1.79)	0.18 (-0.75 - 1.11)	0.36 (-0.58 - 1.30)
16	1.03 (0.20 - 1.87)*	0.77 (-0.18 - 1.65)	0.40 (-0.62 - 1.41)	0.53 (-0.46 - 1.51)
32	0.88 (0.07 - 1.69)*	0.81 (-0.16 - 1.79)	0.61 (-0.38 - 1.59)	0.19 (-0.86 - 1.24)
64	1.01 (-0.15 - 2.17)	1.45 (0.26 - 2.64)*	0.85 (-0.37 - 2.07)	0.41 (-0.91 - 1.72)
125	1.27 (0.10 - 2.44)*	1.21 (-0.40 - 2.83)	1.08 (-0.37 - 2.52)	0.47 (-1.23 - 2.16)
250	1.70 (0.28 - 3.12)*	1.20 (-0.85 - 3.25)	1.33 (-0.41 - 3.08)	0.93 (-0.98 - 2.85)
500	0.74 (-0.85 - 2.33)	2.24 (0.29 - 4.20)*	1.46 (-0.53 - 3.45)	1.08 (-0.87 - 3.03)

* $P \leq 0.05$

Models included age (using categories of age <60 and age 60-69 years), rock drill exposure and impact wrench exposure

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

Next page: **Table S1: All measurements in individual axes:**

Worker[a]	Tool RMS m/s^2	Tool X-ax. m/s^2	(%)[b]	Tool Y-ax. m/s^2	(%)[b]	Tool Z-ax. m/s^2	(%)[b]	Hand RMS m/s^2	Hand X-ax. m/s^2	(%)[b]	Hand Y-ax. m/s^2	(%)[b]	Hand Z-ax. m/s^2	(%)[b]
1	27,6							26,5						
1	25,5							22,6						
1	27,0							23,3						
1	32,2							31,0						
1	25,3							22,6						
2	23,5	20,7	(78)	8,3	(12)	7,4	(10)	14,4	6,7	(22)	5,3	(14)	11,6	(65)
2	24,8	23,0	(86)	7,1	(8)	5,8	(5)	16,6	7,9	(23)	7,0	(18)	12,8	(59)
2	25,4	22,3	(77)	7,9	(10)	9,0	(13)	17,8	10,4	(34)	7,9	(20)	12,0	(45)
2	29,3	24,9	(72)	7,6	(7)	13,5	(21)	25,1	16,8	(45)	8,3	(11)	16,8	(45)
2	26,3	22,8	(75)	7,6	(8)	10,8	(17)	21,1	12,6	(36)	8,5	(16)	14,6	(48)
2	21,9	19,7	(81)	7,3	(11)	6,2	(8)	14,4	6,5	(20)	5,3	(14)	11,7	(66)
2	29,2	24,5	(70)	8,6	(9)	13,3	(21)	25,2	16,7	(44)	9,2	(13)	16,5	(43)
3	32,1	27,9	(76)	9,5	(9)	12,9	(16)	19,5	15,8	(66)	9,3	(23)	6,8	(12)
3	28,5	22,0	(60)	11,2	(15)	14,2	(25)	10,5	8,2	(61)	3,5	(11)	5,5	(27)
3	30,4	26,3	(75)	9,9	(11)	11,5	(14)	15,6	9,2	(35)	5,6	(13)	11,2	(52)
3	29,0	26,0	(80)	9,2	(10)	9,0	(10)	17,2	13,9	(65)	4,8	(8)	8,9	(27)
3	29,2	22,5	(59)	13,0	(20)	13,3	(21)	13,2	10,4	(62)	4,6	(12)	6,8	(27)
4	31,2	27,8	(79)	7,6	(6)	11,9	(15)	18,4	10,2	(31)	10,8	(34)	10,8	(34)
4	29,9	24,4	(67)	10,9	(13)	13,3	(20)	11,6	6,0	(27)	8,4	(52)	5,3	(21)
4	28,7	23,5	(67)	9,4	(11)	13,5	(22)	18,1	13,1	(52)	8,1	(20)	9,6	(28)
4	32,0	26,4	(68)	10,2	(10)	14,0	(19)	25,1	17,1	(46)	12,2	(24)	13,7	(30)
4	28,6	24,9	(76)	10,4	(13)	9,6	(11)	20,6	10,2	(25)	15,2	(54)	9,4	(21)
5	27,9	22,5	(65)	11,0	(16)	12,3	(19)	13,3	9,2	(48)	4,3	(10)	8,6	(42)
5	29,9	25,1	(70)	10,0	(11)	12,8	(18)	16,3	9,7	(35)	6,7	(17)	11,3	(48)
5	29,4	24,3	(68)	9,2	(10)	13,8	(22)	24,1	16,1	(45)	7,2	(9)	16,5	(47)
5	34,4	29,6	(74)	11,9	(12)	12,9	(14)	19,2	9,1	(22)	7,2	(14)	15,2	(63)
5	28,0	23,6	(71)	11,1	(16)	10,0	(13)	14,4	8,6	(36)	5,6	(15)	10,1	(49)
5	28,8	24,2	(71)	9,1	(10)	12,5	(19)	14,0	9,5	(46)	5,6	(16)	8,6	(38)
5	30,4	24,7	(66)	13,2	(19)	11,9	(15)	18,9	12,8	(46)	7,5	(16)	11,7	(38)
Mean1-5:	**28.5**	**24.3**	**(72)**	**9.6**	**(12)**	**11.5**	**(16)**	**19**	**11.1**	**(40)**	**7.4**	**(19)**	**11.1**	**(41)**

[a] Because of a file saving error, the vibration level in the individual X,Y and Z axes for worker 1 was lost. Therefore, only the RMS sum value of the three axes was accessible for worker 1.

[b] Percentage of the total acceleration energy. Example last row (tool-attached accelerometer in x-axis): $(24.3)^2/28.5^2*100=72\%$

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

Table 5 Mixed models: Associations between last 12 months of HAV exposure from rock drills and pegboard score using dominant hand; coefficients represent increase of performance time in the pegboard test (seconds) per tenfold increase in last 12-months exposure before tests ($h \cdot ms^{-2}$)

Age (years)	Coefficient	95% Confidence Interval
20-29	1 REF	
30-39	-0.08	-3.25 to 3.03
40-49	4.89	1.81 to 7.98*
50-59	9.73	6.21 to 13.25*
60-69	15.21	10.55 to 19.88*
Rock drill exposure		
Last year	-0.72	-1.45 to -0.21
Constant	57.06	54.72 to 59.40*

*Significant at p≤0.05

Table 6. Results summary from mixed models at dominant and non-dominant 2nd and 5th fingers at seven test-frequencies: Associations between lifetime cumulative HAV exposure from impact wrenches and VPT; coefficients represent increase of VPT (dB) per tenfold increase in lifetime cumulative exposure ($h \cdot ms^{-2}$)[ab]

Frequency	Dominant 2nd finger (n=147, number of obs = 248) [c d]	Dominant 5th finger (n=146, number of obs = 244) [c d]	Non-dominant 2nd finger (n=144, number of obs = 242) [c d]	Non-dominant 5th finger (n=147, number of obs = 246) [c d]
Hz	Coefficients (95 % CI) [e]	Coefficients (95 % CI) [e]	Coefficients (95 % CI) [e]	Coefficients (95 % CI) [e]
8	0.26 (-0.49 to 1.00)	0.17 (-0.62 to 0.96)	0.10 (-0.60 to 0.79)	0.04 (-0.73 to 0.81)
16	0.65 (-0.09 to 1.39)	0.21 (-0.56 to 0.98)	0.22 (-0.58 to 1.03)	0.34 (-0.40 to 1.09)
32	0.05 (-0.64 to 0.74)	0.17 (-0.62 to 0.96)	0.26 (-0.52 to 1.04)	0.16 (-0.63 to 0.96)
64	0.14 (-0.76 to 1.15)	0.59 (-0.30 to 1.49)	0.46 (-0.51 to 1.44)	0.09 (-0.87 to 1.05)
125	0.21 (-0.76 to 1.17)	0.14 (-0.94 to 1.22)	0.70 (-0.30 to 1.71)	0.29 (-0.91 to 1.48)
250	0.11 (-0.98 to 1.20)	-0.14 (-1.50 to 1.23)	0.20 (-1.01 to 1.41)	0.47 (-0.87 to 1.81)
500	-0.47 (-1.62 to 0.68)	0.23 (-1.29 to 1.74)	0.46 (-0.98 to 1.90)	0.55 (-0.91 to 2.02)

* *$p \leq 0.05$*

[a] Log10-transformed exposure was used in models adjusted for age in 10-year intervals.

[b] HAV exposure was calculated as lifetime cumulative exposure at each VPT-test. Subject ID was used as random intercept in linear mixed models

[c] Each subject was tested for VPT 1 – 3 three times (mean 1.7 times) with approx. two years between each test.

[d] The number of participants is less than the total of n=148 for each tested finger because of participants having injured or missing fingertips

[e] Impact wrench exposure was adjusted for rock drill exposure in the models

Table 7. Results summary from mixed models at dominant and non-dominant 2nd and 5th fingers at seven test-frequencies: Associations between HAV exposure from impact wrenches and VPT; coefficients represent increase of VPT (dB) per tenfold increase in last 12-months exposure before tests (h · ms^{-2})[a,b]

Frequency	Dominant 2nd finger (n=147, number of obs = 248) [c,d]	Dominant 5th finger (n=146, number of obs = 244) [c,d]	Non-dominant 2nd finger (n=144, number of obs = 242) [c,d]	Non-dominant 5th finger (n=147, number of obs = 246) [c,d]
Hz	Coefficients (95 % CI) [e]	Coefficients (95 % CI) [e]	Coefficients (95 % CI) [e]	Coefficients (95 % CI) [e]
8	-0.44 (-1.29 to 0.41)	-0.46 (-1.39 to 0.47)	-0.40 (-1.22 to 0.43)	-0.45 (-1.35 to 0.44)
16	0.08 (-0.76 to 0.92)	-0.35 (-1.24 to 0.55)	-0.27 (-1.22 to 0.68)	0.08 (-0.79 to 0.96)
32	0.05 (-0.72 to 0.83)	-0.07 (-0.99 to 0.86)	-0.05 (-0.95 to 0.84)	0.05 (-0.88 to 0.97)
64	0.16 (-0.85 to 1.18)	0.29 (-0.76 to 1.35)	0.61 (-0.51 to 1.75)	0.38 (-0.73 to 1.49)
125	0.28 (-0.83 to 1.39)	-0.38 (-1.70 to 0.93)	0.08 (-1.11 to 1.26)	0.39 (-1.01 to 1.79)
250	-0.21 (-1.47 to 1.06)	-0.39 (-1.99 to 1.21)	-0.45 (-1.87 to 0.98)	0.23 (-1.39 to 1.84)
500	-0.21 (-1.54 to 1.13)	0.22 (-1.58 to 2.01)	0.16 (-1.48 to 1.80)	0.45 (-1.31 to 2.22)

* *$p \leq 0.05$*

[a] Log10-transformed exposure was used in models adjusted for age in 10-year intervals.

[b] HAV exposure was calculated as average exposure during the last year before the VPT-test. Subject ID was used as random intercept in linear mixed models

[c] Each subject was tested for VPT 1 – 3 three times (mean 1.7 times) with approx. two years between each test.

[d] The number of participants is less than the total of n=148 for each tested finger because of participants having injured or missing fingertips

[e] Impact wrench exposure was adjusted for rock drill exposure in the models

Table 8. Mixed models: Associations between lifetime cumulative HAV exposure from rock drills and pegboard score using non-dominant hand; coefficients represent increase of performance time in the pegboard test (seconds) per tenfold increase in lifetime cumulative exposure (h · ms^{-2})

Age (years)	Coefficient	95% Confidence Interval
20-29	1 REF	
30-39	2.64	-1.76 to 6.84
40-49	6.37	2.27 to 10.47*
50-59	10.70	5.85 to 15.43*
60-69	21.8	15.72 to 27.92*
Rock drill exposure		
Lifetime cumulative	-0.60	-1.38 to 0.18
Constant	61.4	58.3 to 64.5 *

*Significant at p≤0.05

Table 9. Mixed models: Associations between last 12-months HAV exposure from rock drills and pegboard score using non-dominant hand; coefficients represent increase of performance time in the pegboard test (seconds) per tenfold increase in exposure last year (h · ms^{-2})

Age (years)	Coefficient	95% Confidence Interval
20-29	1 REF	
30-39	2.72	-1.43 to 6.86
40-49	6.26	2.22 to 10.31*
50-59	10.36	5.62 to 15.10*
60-69	21.2	15.07 to 27.24*
Rock drill exposure		
Last year	-0.98	-1.92 to -0.04*
Constant	61.7	58.7 to 64.7 *

*Significant at p≤0.05

Table 10. Mixed models: Associations between lifetime cumulative HAV exposure from impact wrenches and pegboard score using dominant hand; coefficients represent increase of performance time in the pegboard test (seconds) per tenfold increase in lifetime cumulative exposure (h · ms^{-2})

Age (years)	Coefficient	95% Confidence Interval
20-29	1 REF	
30-39	-0.25	-3.45 to 2.93
40-49	4.84	1.67 to 8.00*
50-59	9.64	5.95 to 13.33*
60-69	15.52	10.81 to 20.23*
Impact wrench exposure		
Lifetime cumulative	0.42	-0.32 to 1.16
Constant	55.7	53.5 to 57.9 *

*Significant at p≤0.05

Table 11. Mixed models: Associations between lifetime cumulative HAV exposure from impact wrenches and pegboard score using non-dominant hand; coefficients represent increase of performance time in the pegboard test (seconds) per tenfold increase in lifetime cumulative exposure (h · ms^{-2})

Age (years)	Coefficient	95% Confidence Interval
20-29	1 REF	
30-39	2.64	-1.59 to 6.87
40-49	6.92	2.73 to 11.11*
50-59	11.53	6.54 to 16.52*
60-69	22.57	16.36 to 28.78*
Impact wrench exposure		
Lifetime cumulative	-0.30	-1.25 to 0.66
Constant	60.6	57.7 to 63.5 *

*Significant at p≤0.05

Table 12. Mixed models: Associations between last 12-months exposure from impact wrenches and pegboard score using dominant hand; coefficients represent increase of performance time in the pegboard test (seconds) per tenfold increase in exposure last 12 months (h · ms^{-2})

Age (years)	Coefficient	95% Confidence Interval
20-29	1 REF	
30-39	-0.29	-3.49 to 2.92
40-49	4.90	1.71 to 9.10*
50-59	9.90	6.25 to 13.56*
60-69	15.85	11.20 to 20.50*
Impact wrench exposure		
Last year	-0.41	-0.64 to 1.45
Constant	55.9	53.8 to 58.0 *

*Significant at p≤0.05

Table 13 Mixed models: Associations between last 12-months HAV exposure from impact wrenches and pegboard score using non-dominant hand; coefficients represent increase of performance time in the pegboard test (seconds) per tenfold increase in exposure last 12 months (h · ms^{-2})

Age (years)	Coefficient	95% Confidence Interval
20-29	1 REF	
30-39	2.53	-1.71 to 6.77
40-49	6.52	2.30 to 10.74*
50-59	10.91	5.96 to 15.85*
60-69	22.16	16.03 to 28.29*
Impact wrench exposure		
Last year	0.19	-1.18 to 1.57
Constant	60.3	57.5 to 63.1 *

*Significant at p≤0.05