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Original article

Quantitative Assessment of Work-related Hand-arm Vibration Exposure Among Workers in the Construction, Underground Coal Mining, Wood Working, and Metal Working Industry: The German Hand-arm Vibration Study

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ABSTRACT

Background: Standardized exposure assessments were conducted to quantify the historical occupational exposure to hand-arm vibration of workers in the German construction, underground coal mining, woodworking, and metalworking industries.

Methods: A two-step approach was used to assess historical vibration exposure. In the first step, individual work histories were reconstructed by standardized personal interviews. The interview focused on the identification of relevant power tools used throughout the working life. In the second step, an equipment-exposure-matrix was constructed by industrial hygiene measurements. By linking the power tools in the work history to the equipment-exposure-matrix, individual daily, and long-term vibration exposures can be quantified.

Results and conclusions: A total of 423 power tools were identified for 5,115 exposure segments over a period of 50 years. 97.2% of the vibration values were based on industrial hygiene measurements. The total vibration value (a_{hv}) of the power tools used varied between 0.8 m/s^2 and 65.2 m/s^2 with a median value of 14.2 m/s^2. The median value of cumulative vibration exposure is D_{hv} = 121,971 (range: 23-3,374,640) m^2/s^4·day, corresponding to a daily vibration exposure of $a_{hv(8)}$ = 7 m/s^2 for 2489 working days (11.3 years).

This study provides a detailed description of hand-arm vibration exposure among workers in the related industries studied. Our analyses indicate that the quantification of daily vibration exposure is often uncertain and should be interpreted with caution. In contrast, cumulative vibration exposure is a more reliable exposure parameter for describing general working conditions and for guiding the prevention and compensation of vibration-related health problems.

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1. Introduction

Mechanical vibration arises from a wide variety of occupational activities in mining, construction, metalworking, woodworking, and forestry. Hand-arm vibrations occur when using hand-held and hand-guided power tools and are the cause of significant health impairments, such as painful and disabling conditions of the upper limbs [1–3]. In Germany, there were approximately 1.5 to 2 million workers exposed to hand-arm vibrations that could endanger their health [4]. Health-related effects of hand-arm vibration exposure have 3 main clinical components: vascular, neurological, and musculoskeletal disorders [2].

Vascular and neurological disorders often overlap in occurrence and are the most extensively studied forms of hand-arm vibration syndrome [2,5,6]. In contrast, vibration-induced musculoskeletal disorders of the upper extremities have not been well studied to date. Early studies and reviews indicate an elevated risk of musculoskeletal symptoms (upper limb pain, stiffness, and muscle tendon syndrome) and osteoarthritis (OA) of the upper limb among vibration-exposed workers in comparison to nonexposed workers [1,3,6–10]. However, an exposure-response relationship between hand-arm-vibration exposure and musculoskeletal disorders has yet to be well-established in published studies, especially when objective diagnoses are considered as the relevant outcome instead of clinical symptoms [6].

To quantitatively assess the effect of work-related hand-arm vibration exposure on the risk of musculoskeletal disorders of the upper extremities, the German hand-arm vibration study was conducted. The German hand-arm vibration study is an industry-based case-control study. As described previously [11], the cases and controls in this study were recruited from members of the German Social Accident Insurance institutions in the construction, underground coal mining, metal-, and wood-working industries during the time between January 1, 2010, and November 30, 2021. The cases are consecutive patients with musculoskeletal disorders who were suspected by local physicians of having the legal occupational disease with the number 2103. Occupational disease no. 2103 is a group of musculoskeletal disorders defined as having one of the following six clinical diagnoses: OA of the hand, OA of the elbow, OA of the shoulder, Kienböck's disease, scaphoid fracture/scaphoid pseudoarthrosis, and elbow osteochondrosis. If a local physician suspects that the patient may meet the criteria for occupational disease No. 2103, he will send these patients to the German Social Accident Insurance institutions for further investigation. The controls were selected as a random sample of all types of newly reported compensable occupational injuries (injuries with at least three days' absence from work). Both cases and controls had jobs involving exposure to hand-arm vibration.

In this study, we would like to describe in detail the exposure assessment methods used in this study and discuss some important issues for a valid quantification of work-related hand-arm vibration exposure over time. In addition, typical exposure conditions (daily working time, type of vibrating machines used, daily and long-term vibration exposures) in the related industries are also described in detail using the control group of the German hand-arm vibration study.

2. Materials and methods

The assessment of work-related hand-arm vibration exposure in this study was carried out in the same way for cases and controls. As described previously (11), the controls are a random sample of all newly reported compensable occupational injuries (not all workers) in the related industries. They were selected separately for different industries and matched 1:3 with the cases by year of birth, sex, and reporting year (same reporting year of the injury for the controls and occupational disease number 2103 for the cases). Therefore, only male controls were recruited for this study. In comparison to the cases (66% response rate), the controls have a relatively lower response rate (20.4%).

The exposure assessment in this study focused mainly on 2 steps: the reconstruction of individual work histories and the establishment of an equipment exposure matrix (a machine vibration exposure database).

2.1. Reconstruction of individual work history and identification of relevant power tools

For reconstruction of individual work history, standardized personal interviews were carried out by specially trained safety engineers from the German Social Accident Insurance institutions. These engineers have more than 10 years' working experience und have comprehensive knowledge about the work organization, work process, power tools, and materials used at workplaces in the related industrial sectors.

The personal interview focuses mainly on the identification of relevant power tools used throughout the working life, including:

- The name of the tools and related production information (such as manufacturer, type of drive, rated power, etc.)
- Task, work process, and raw materials used
- Daily working time with power tools, working days with power tools per week, and working weeks per year.

2.2. Establishment of an equipment-exposure-matrix for quantifying hand-arm vibration exposure

An exposure matrix (exposure database) of power tool vibrations for quantifying hand-arm vibration exposure has been established and continually extended by the German Social Accident Insurance since the mid-1980s. The database currently consists of more than 700 hand-held power tools. Their vibration values were measured based on standardized industrial hygiene measurement protocols with a frequency range between 4 and 1250 Hz under real operating conditions. Besides the vibration values, information about the working process and working materials were also documented. This information is essential for quantifying work-related vibration exposures, as vibration exposures vary greatly when power tools are used on different working materials and for different purposes.

In addition, product information for the power tools (including manufacturer, year, weight, drive type, rated power, rotational speed, etc.) was included in the database if this information was available.

2.3. Determining hand-arm vibration exposure values

By combining the power tools identified in the work history with the information stored in the equipment-exposure-matrix, detailed exposure values were quantified for the entire working life of each study participant.

The vibration generated by the power tools was measured in 3 orthogonal directions (x, y, and z) according to the international standard ISO 5349-1:2001 [12]. Vibration values are expressed as accelerations a_{hwx}, a_{hwy}, and a_{hwz} in the three measuring directions. The vibration total value (a_{hv}) is determined as the root-sum-of-squares of the 3 component values (a_{hwx}, a_{hwy}, and a_{hwz}):

$$a_{hv} = \sqrt{{a_{hwx}}^2 + {a_{hwy}}^2 + {a_{hwz}}^2} \quad (1)$$

The daily vibration exposures from using various power tools at different time periods of a day are quantified according to the international standard ISO 5349-1:2001 [12] and expressed in terms of 8-hour energy-equivalent root-sum-of-squares of the related acceleration magnitude:

$$a_{hv(8)} = \sqrt{\frac{1}{T_0}\sum_{i=1}^{n} a_{hvi}^2 T_i} \quad (2)$$

$$a_{hw(8)} = \sqrt{\frac{1}{T_0}\sum_{i=1}^{n} a_{hwi}^2 T_i} \quad (3)$$

where

$a_{hv(8)}$ = daily vibration total value of 3 measuring directions
$a_{hw(8)}$ = daily vibration value in the direction along the forearm
T_0 = reference duration of 8 hours (conventional daily working time)
T_i = daily working hours of using power tool i
a_{hvi} = frequency weighted acceleration total value of 3 measuring directions of the power tool i
a_{hwi} = frequency weighted acceleration value in the direction along the forearm of the power tool i
n = total number of power tools used in a day

The long-term cumulative hand-arm vibration exposure is quantified in a manner comparable to that of whole-body vibration as described in the German guideline VDI 2057-Part 1 [13] and are expressed as the sum-of-squares of daily vibration exposure over the course of an entire study period:

$$D_{hv} = \sum a_{hvi(8)}^2 \, d_i \quad (4)$$

$$D_{hw} = \sum a_{hwi(8)}^2 \, d_i \quad (5)$$

where

D_{hv} = long-term cumulative vibration exposure in 3 measuring directions
D_{hw} = long-term cumulative vibration exposure in the direction along the forearm
$a_{hvi(8)}$ = daily vibration exposure of 3 measuring directions at day i
$a_{hwi(8)}$ = daily vibration exposure in the direction along the forearm at day i
d_i = number of working days with a daily exposure of $a_{hvi(8)}$

For a better understanding of the mathematical equations given above and to describe some of the uncertainties involved in quantifying historical vibration exposure in practice, an example is given in Fig. 1.

Suppose a worker has had 2 employment periods (A, B). Each employment period had a duration of 10 years (corresponding to 2200 working days [14]) as shown in Fig. 1. A total of 4 power tools were used, 1 power tool in period A and 3 power tools in period B. The acceleration values of the power tools and their corresponding working days are also given in Fig. 1. Assume that the daily working time of each power tool is 1 hour. Then the daily vibration exposure value in employment period A can be easily calculated as $a_{hv(8)} = 2.8$ m/s^2 for 1000 working days (s. Fig. 1).

In employment period B, different combinations of the use of the 3 power tools can lead to different values of the daily vibration exposure as some power tools are used less frequently than others throughout the whole employment period. An extreme scenario (scenario 1, best case) is that only 1 power tool is used on a working

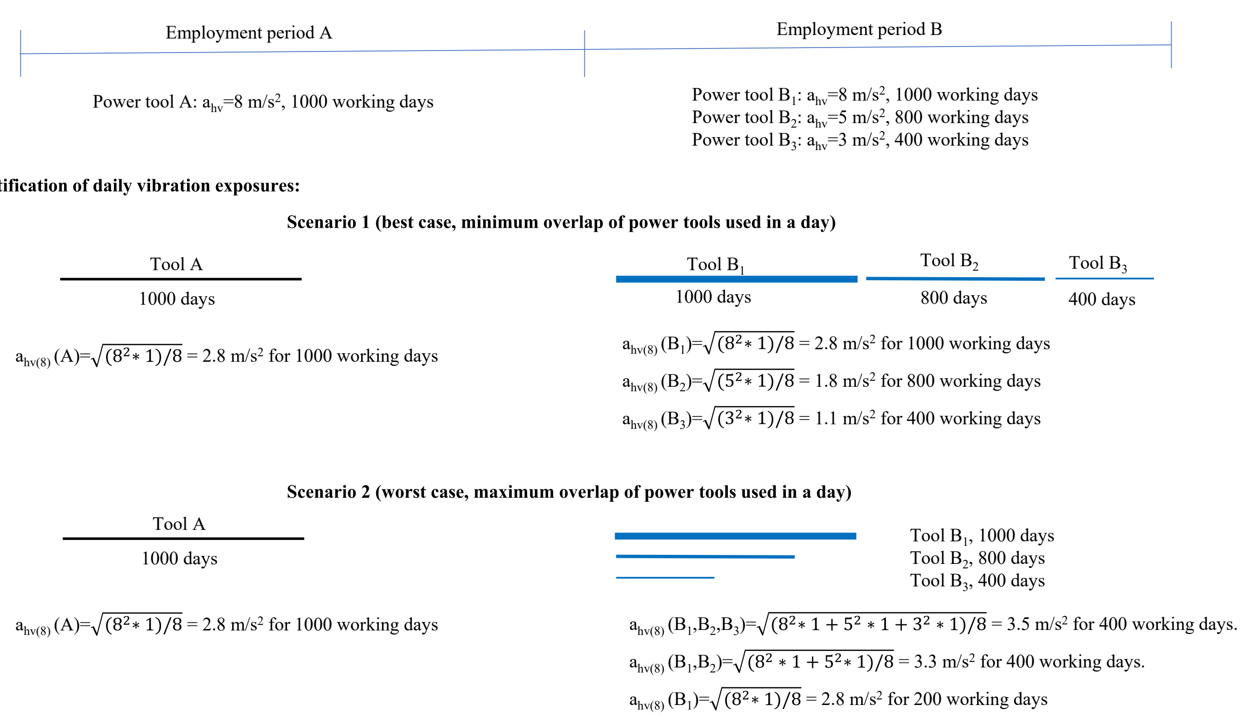

Fig. 1. Example of quantifying daily and long-term vibration exposures.

day. Then the daily vibration exposure value can be calculated as $a_{hv(8)} = 2.8$ m/s^2 for 1000 working days, 1.8 m/s^2 for 800 working days, and 1.1 m/s^2 for 400 working days (s. Fig. 1). Another extreme scenario (scenario 2, worst case) is that there is a maximum overlap in the daily use of the 3 power tools as shown in Fig. 1. Then the daily vibration exposure value can be calculated as $a_{hv(8)} = 3.5$ m/s^2 for 400 working days, 3.3 m/s^2 for 400 working days, and 2.8 m/s^2 for 200 working days. In this study, when there is uncertainty, the worst-case scenario (maximum overlap in the daily use of different power tools) has been used in the quantification of daily vibration exposure values.

The quantification of the long-term cumulative vibration exposure (D_{hv}) is independent of the scenarios described above. For both the best- and the worst-case scenarios in the example in Fig. 1, the long-term cumulative vibration exposure (employments A + B) can be calculated as

$$D_{hv} = \left(8^2*1*1000\right) \Big/ 8 + \left(8^2*1*1000\right) \Big/ 8 + \left(5^2*1*800\right) \Big/ 8 + \left(3^2*1*400\right) \Big/ 8 = 18950\ \mathrm{m}^2 \Big/ \mathrm{s}^4 \cdot \mathrm{day}$$

2.4. Statistical analysis

We described the common levels of exposure to hand-arm vibration in different industries by using descriptive statistics. Exposure levels were only quantified for the control group, as this is a randomly selected sample of all types of compensable occupational injury (matched to the cases by birth year). Our previous analysis showed that the hand-arm vibration exposure of the controls was not associated with their occupational injuries (11). Therefore, the exposure level of the control group is more likely to reflect the exposure status of workers exposed to hand-arm vibration in these industries. Continuous variables were described using nonparametric statistics such as median and range (as the data are not normally distributed), and categorical variables were described using frequencies. The distribution (proportions) of the acceleration values (a_{hv} and a_{hw}) of the power tools used in a total of 3,252 exposure segments and the distribution (proportions) of the long-term cumulative vibration exposure of the control subjects, were plotted to give an overall picture of the exposure conditions in these industries.

All statistical analyses were performed using SAS version 9.4.

3. Results

In total, 823 male participants (209 cases, 614 controls) were recruited for this study. The individual work histories of the study sample contain 2,107 employment periods with 5,115 exposure segments. As described previously (11), the control group is a random sample of all types of compensable occupational injuries with an average age of 52 years (range: 22-83 years; 93%: 40-70 years). The individual work histories of the control subjects contain 1,396 employment periods with 3,252 exposure segments over an exposure period of approximately 50 years. Each control person had a median of 4 exposure segments with a maximum of 62. A total of 423 power tools were identified as a source of exposure to hand-arm vibration through personal interviews. They were divided into 15 power tool groups as shown in Table 1. Hammers (44.4%), screwdrivers (16.6%), grinders (14.8), compressors (11.3%), saws (5.6%), and drills (3.3%) were the most commonly used power tools in the industries analyzed.

The vibration values of the power tools identified in the individual work histories were quantified using the above-described equipment-exposure-matrix. Table 1 describes the quality of the exposure data provided for the 5,115 exposure segments. 97.2% of the vibration values were based on standardized industrial hygiene measurements of comparable tools, 2.7% were based on vibration values of similar tools, and only 0.01% were based on vibration values of tools with the same name, use, and working materials.

The daily working time of each power tool (used in the control group) and the corresponding acceleration values are shown in Table 2. In about 50% of the exposure segments, power tools were used for less than 30 minutes per day. In about 75% of the exposure segments, power tools were used for less than 1 hour, and in 93% of the segments for less than 2 hours. Compared to construction, wood, and metal industries, the daily working time with power tools in underground coal mining is even much

Table 1
Power tools used and quality parameters of the exposure values in different industrial sectors

	Construction	Underground coal mining	Wood/metalworking	Total
N	264	416	143	823
Total number of exposure segments	2654	1789	672	5115
Individual number of exposure segments				
Median (range)	8 (1 – 26)	4 (1 – 20)	3 (1 – 48)	4 (1 – 62)
Power tool groups				
Drills	104 (3.9%)	33 (1.8)	30 (4.5%)	167 (3.3%)
Milling machines	28 (1.1%)	6 (0.3%)	4 (0.6%)	38 (0.7%)
Hammers	1094 (41.2%)	1024 (57.2%)	153 (22.8%)	2271 (44.4%)
Binder	46 (1.7%)	0	7 (1.0%)	53 (1.0%)
planer machine	3 (0.1%)	0	1 (0.2%)	4 (0.1%)
Nibblers	4 (0.2%)	0	0	4 (0.1%)
Mixers	60 (2.3%)	0	0	60 (1.2%)
Riveting tools	0	4 (0.2%)	14 (2.1%)	18 (0.4%)
Surface cleaner	5 (0.2%)	1 (0.1%)	1 (0.2%)	7 (0.1%)
Saws	243 (9.2%)	0	43 (6.4%)	286 (5.6%)
Grinders	409 (15.4%)	59 (3.3%)	288 (42.9%)	756 (14.8%)
Cutters	11 (0.4%)	0	9 (1.3%)	20 (0.4%)
Screwdriver	73 (2.8%)	660 (36.9%)	115 (17.1%)	848 (16.6%)
Compressor	569 (21.5%)	1 (0.1%)	7 (1.0%)	577 (11.3%)
Special designs	5 (0.2%)	1 (0.1%)	0	6 (0.1%)
Quality parameter of exposure values				
Direct measurements	2524 (95.1%)	1789 (100%)	656 (97.6%)	4969 (97.2%)
Similar devices*	124 (4.7%)	0	16 (2.4%)	140 (2.7%)
Devices with the same use†	6 (0.2%)	0	0	6 (0.1%)

* Exposure values based on power tools with the same designation, use, working material, and in the same category of weight, power, and rotational speed.
† Exposure values based on power tools with the same designation, use, and working material.

Table 2
Daily working time and acceleration values of the power tools used (control group only)

	Construction	Underground coal mining	Wood/Metalworking	Total
Number of exposure segments	1693	1228	331	3252
Daily working time of each power tool (hour)				
Median (range)	0.80 (0.04-8.00)	0.24 (0.07-4.00)	0.80 (0.08-4.80)	0.50 (0.04-8.00)
25% - 75%	0.40-1.60	0.16-0.40	0.50-1.20	0.24 – 1.00
a_{hv} (m/s^2)*				
Median (range)	10.3 (0.8-65.2)	27.7 (1.4-58.2)	8.0 (0.8-47.9)	14.2 (0.8-65.2)
25% - 75%	6.5-16.0	14.2-58.2	5.5-14.8	7.8-23.5
a_{hw} (m/s^2)†				
Median (range)	7.5 (0.3-59.2)	12.1 (1.0-37.3)	6.0 (0.3-38.7)	8.5 (0.3-59.2)
25% - 75%	3.8-11.2	4.0-23.6	3.6-9.8	4.0-12.7

* a_{hv} = acceleration values in a total of 3 measuring directions.
† a_{hw} = acceleration values only in the direction along the forearm.

shorter (less than 50% of the daily working time in the other industries). However, the acceleration values (a_{hv}) of the power tools used in underground coal mining are on average about 3 times higher than in the construction, wood, and metal industries. A distribution of the acceleration values of the power tools used in the different industries is shown in Fig. 2. In general, there is no difference in the acceleration values of the power tools used in the construction, woodworking, and metalworking industries. However, the acceleration values of the power tools used in underground coal mining are systematically higher.

Table 3 shows the daily and long-term cumulative vibration exposures of the control group. As individual daily vibration exposures change over time, only the highest daily vibration exposure is shown. The highest daily vibration exposure is on average about $a_{hv(8)} = 10.1$ m/s^2 with the highest value in underground coal mining ($a_{hv(8)} = 12.1$ m/s^2) and the lowest values in the wood and metal-working industries ($a_{hv(8)} = 5.3$ m/s^2). The average long-term cumulative vibration exposure is about $D_{hv} = 239{,}220$ $m^2/s^4 \cdot day$ with the highest value in underground coal mining ($D_{hv} = 323{,}581$ $m^2/s^4 \cdot day$) and the lowest value in wood and metal working ($D_{hv} = 143{,}707$ $m^2/s^4 \cdot day$).

Fig. 3 shows the distribution of long-term cumulative vibration exposure in different industries. The long-term vibration exposure (D_{hv}) of workers in the construction, woodworking, and metalworking industries are quite similar. For a better understanding of the meaning of the long-term vibration exposure given in Table 3 and Fig. 2, we present Table 4.

Table 4 shows not only the distribution of long-term cumulative vibration exposure but also the practical meaning of these exposure values. For example, Table 4 shows that 80% of the study sample have a long-term cumulative vibration exposure corresponding to a daily vibration exposure of $a_{hv(8)} = 7$ m/s^2 for more than 1579 working days (7 working years), and 60% of the study sample have a long-term cumulative vibration exposure corresponding to a daily vibration exposure of $a_{hv(8)} = 7$ m/s^2 for more than 3768 working days (17 working years). These values can be easily understood to describe the exposure conditions in these industries.

4. Discussion

Prolonged occupational exposure to hand-transmitted vibration is known to cause a range of disabling clinical disorders of the vascular, neurological and musculoskeletal components of the hands and upper limbs. This condition has been studied extensively over the past century, with the emphasis on the application of control measures to reduce the harmful effects of hand-transmitted vibration. Up to date, a large number of studies have been published describing occupational exposure to hand-arm vibration in various industries and occupational groups, especially when studying vibration-induced white finger, such as metal workers [6], quarry and foundry workers [15,16], road workers [17,18], construction workers [19], shipyard workers [20], forestry chainsaw operators [8,18,21], ground maintenance equipment operators [22], and so on. However, most of these studies provide only limited exposure information (a few numbers of power tools used with the estimated daily vibration exposure, and in a few studies also the long-term cumulative vibration exposures) and cannot provide an entire picture of vibration exposure in these industries.

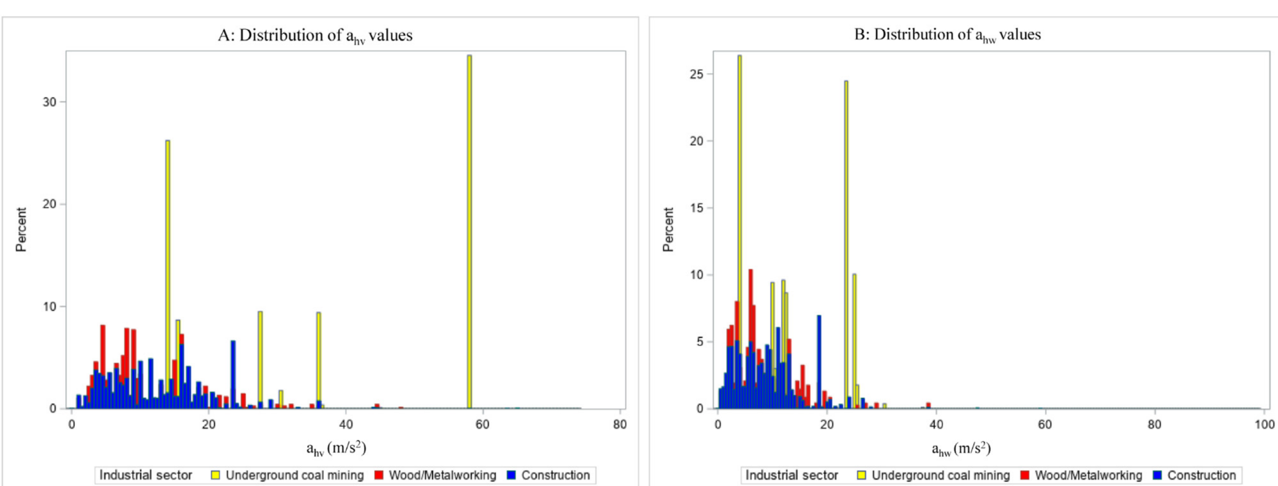

Fig. 2. Distribution of acceleration values (a_{hv}/a_{hv}) of the power tools used in the total of 5115 exposure segments.

Table 3
Daily and long-term cumulative hand-arm-vibration exposure (control group only)

	Construction	Underground coal mining	Wood/metalworking	Total
N	185	326	103	614
Highest daily exposure ever				
$a_{hv(8)}$ (m/s^2)*				
Median (range)	8.6 (0.3-22.4)	10.9 (0.9-34.4)	4.5 (0.4-21.3)	10.1 (0.3-34.4)
25% - 75%	5.8-12.4	8.7-13.7	2.4-7.6	6.1 – 13.0
$a_{hw(8)}$ (m/s^2)†				
Median (range)	6.0 (0.1-20.1)	5.0 (0.3-14.3)	3.2 (0.2-11.2)	5.1 (0.1-20.1)
25% - 75%	4.4-8.7	3.6-6.8	1.7-5.1	3.4-7.1
Long-term cumulative exposure				
D_{hv} ($m^2/s^4 \cdot day$)‡				
Median (range)	75,479 (23-2,110,830)	218,390 (188-3,374,640)	42,128 (48-1,927,140)	121,971 (23-3,374,640)
25% - 75%	21,299–166,901	74,763–396,285	13,159–175,495	32,026–298,711
D_{hw} ($m^2/s^4 \cdot day$)§				
Median (range)	38,649 (3-1,703,240)	40,214 (17-643,178)	20,870 (33-1,092,600)	37,509 (3-1,703,240)
25% - 75%	11,675–88,845	11,772–84,385	5,499–91,299	10,452–86,841

* $a_{hv(8)}$ = daily vibration exposure in a total of 3 measuring directions.
† $a_{hw(8)}$ = daily vibration exposure in the direction along the forearm.
‡ D_{hv} = long-term cumulative vibration exposure in a total of 3 measuring directions.
§ D_{hw} = long-term cumulative vibration exposure in the direction along the forearm.

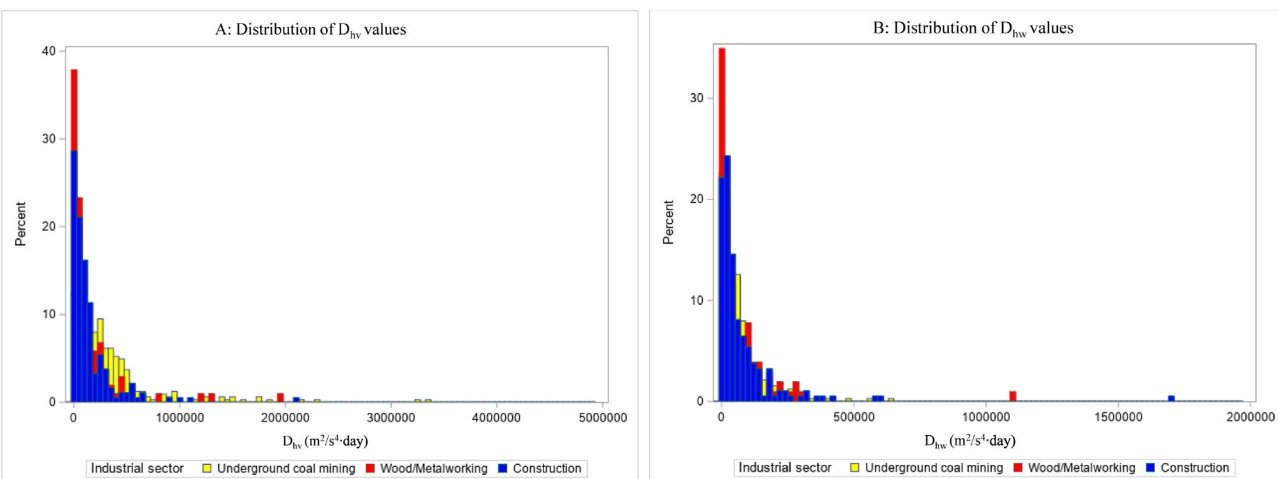

Fig. 3. Distribution of long-term vibration exposure in 614 controls.

Table 4
Distribution of long-term cumulative vibration exposure in the control group

Long-term cumulative vibration exposure	Expected working days at a given average daily vibration exposure ($a_{hv(8)}$ or $a_{hw(8)}$)*			
	$a_{hv(8)}$ ($a_{hw(8)}$)* = 3 m/s^2	$a_{hv(8)}$ ($a_{hw(8)}$)* = 5 m/s^2	$a_{hv(8)}$ ($a_{hw(8)}$)* = 7 m/s^2	$a_{hv(8)}$ ($a_{hw(8)}$)* = 9 m/s^2
D_{hv} ($m^2/s^4 \cdot day$)†				
1st quintile: ≤21,935	≤2,437 days (11 yrs.)	≤877 days (4 yrs.)	≤448 days (2 yrs.)	≤271 days (1 yrs.)
2nd quintile: ≤77,359	≤8,595 days (39 yrs.)	≤3,094 days (14 yrs.)	≤1,579 days (7 yrs.)	≤955 days (4 yrs.)
3rd quintile: ≤184,649	—	≤7,386 days (34 yrs.)	≤3,768 days (17 yrs.)	≤2,280 days (10 yrs.)
4th quintile: ≤355,975	—	—	≤7,265 days (33 yrs.)	≤4,395 days (20 yrs.)
5th quintile: ≤3,374,640	—	—	—	—
D_{hw} ($m^2/s^4 \cdot day$)‡				
1st quintile: ≤7,462	≤829 days (4 yrs.)	≤298 days (1 yrs.)	≤152 days (0.7 yrs.)	≤92 days (0.4 yrs.)
2nd quintile: ≤21,055	≤2,239 days (10 yrs.)	≤842 days (4 yrs.)	≤430 days (2 yrs.)	≤260 days (1 yrs.)
3rd quintile: ≤50,788	≤5,643 days (26 yrs.)	≤2,032 days (9 yrs.)	≤1,036 days (5 yrs.)	≤627 days (3 yrs.)
4th quintile: ≤103,633	≤11,514 days (52 yrs.)	≤4,145 days (19 yrs.)	≤2,115 days (10 yrs.)	≤1,279 days (6 yrs.)
5th quintile: ≤1,703,240	—	—	—	—

* $a_{hv(8)}$ ($a_{hw(8)}$) = daily vibration exposure in a total of 3 measuring directions (only in the direction along the forearm).
† D_{hv} = long-term cumulative vibration exposure in a total of 3 measuring directions.
‡ D_{hw} = long-term cumulative vibration exposure in the direction along the forearm.

In contrast, this study provides the first systematic and quantitative assessment of hand-arm vibration exposure in a large sample of exposed workers in the German construction, underground coal mining, woodworking, and metalworking industries. We identified almost all power tools commonly used in these industries, including their daily working time, frequency of use, acceleration values, and daily and long-term cumulative vibration exposures. This information provides an overall picture of the vibration exposure in these industries. Based on the estimated exposure-response relationship (11), the exposure information provided in this study can be used to make recommendations for the prevention and compensation of vibration-related health problems.

Exposure assessment is the most important and difficult part of an occupational epidemiological study. Recall bias and objective assessment of historical exposure data are the common challenges in assessing historical occupational exposures. In the absence of detailed historical employment records, personal interviews have to be conducted, and recall bias is usually unavoidable, especially when exposure duration is estimated subjectively. Previous analysis has shown that the duration of vibration exposure tends to be greatly overestimated [23]. Involving specially trained safety engineers in the personal interviews, differentiating between the duration of use and the duration of contact, and carrying out plausibility checks, can be expected to reduce recall bias.

In this study, the personal interviews focus mainly on the collection of relevant data for the power tools used in the workplaces. As described above, the face-to-face interviews were carried out by specially trained safety engineers who have extensive knowledge of the work process and the power tools and materials used in these industries. This knowledge is crucial for accurately formulating target questions and assessing the plausibility of responses during the face-to-face interview. This minimizes the potential for recall bias. These engineers are also responsible for linking the power tools identified in the work history to the equipment-exposure-matrix. This is very important because the same power tools can have different vibration levels when used on different materials. These engineers ensure the correct assignment of the power tools used in the work history and in the exposure matrix, and thus a valid assessment of the historical vibration exposures.

For the first time in an occupational epidemiological study, an exposure matrix was used to objectively quantify daily and long-term vibration exposures. For a total of 5,115 exposure segments of the 823 study participants, 97% of the exposure data were based on industrial hygiene measurements in the field under real operating conditions according to the international standard [12]. Only 0.01% ($n = 6$) of the exposure data were based on exposure values from similar power tools. The exposure assessment method used in this study therefore provides a standardized, objective, and valid quantification of work-related hand-arm vibration exposures.

In order to better describe the common levels of occupational exposure to hand-arm vibration in the related industries, we focused our analyses only on the control group. The control group is a random sample of all types of compensable occupational injuries. Our previous analyses showed that their injuries were not associated with exposure to hand-arm vibration [11]. Therefore, the exposure to hand-arm vibration among workers with compensable occupational injuries would be expected to be the same as in the population of all exposed workers (with the same age structure as the controls in this study) in these industries. As the control group in this study is age-matched to the cases, the exposure levels reported for the control group can only be used to a limited extent to represent general working conditions in the related industries.

Unlike the controls, we deliberately do not provide exposure data for the cases. The cases are individuals suspected of having vibration-induced musculoskeletal disorders. Their daily and long-term vibration exposures have been published previously (11). On average, the long-term cumulative vibration exposures of the cases are about 50% higher than those of the controls. As musculoskeletal disorders of the upper limbs are associated with hand-arm vibration exposure, the exposure data of the cases cannot be used to describe the general exposure conditions of these industries and were therefore excluded from the data analyses.

Our analyses showed that 75% of the power tools used in these industries have an acceleration value of $a_{hv} > 7.8$ m/s^2, and in underground coal mining even >14 m/s^2. More than 73% of the study sample had a daily vibration exposure above the current exposure limit in Germany ($a_{hv(8)} = 5$ m/s^2 [8]) for more than 1 year (corresponding to 220 working days). However, as described in Fig. 1, the quantification of historical daily vibration exposure can be uncertain when more than one power tool is used during the same work period. In this study, 1,396 work periods were identified for the 614 individuals in the control group. For 522 (85%) of the controls, more than one power tool was used during the same work period in their work history. Since we don't know whether these power tools were used on the same day, the worst-case assumption (maximum overlap of daily use of different power tools, see Fig. 1) for quantifying daily vibration exposure is likely to lead to an overestimation of daily vibration exposure in this study. As described in the Methods section, this problem does not affect the quantification of long-term cumulative vibration exposures. The distribution of long-term vibration exposures shows that 50% of the workers in the control group have a long-term vibration exposure of $D_{hv} > 121{,}971$ m^2/s^4·day, corresponding to a daily vibration exposure of $a_{hv(8)} = 7$ m/s^2 for 2489 working days (11.3 years).

Overall, this study provides the first detailed description of hand-arm vibration exposure among workers in the construction, underground coal mining, woodworking, and metalworking industries in Germany. The use of an objective exposure database to quantify historical vibration exposure in this study allows for a good retrospective assessment. The exposure data provided in this study may also partly reflect the working conditions in other European countries. Our analyses indicate that the quantification of historical daily vibration exposure is often uncertain and should be interpreted with caution. The long-term cumulative vibration exposure is a more reliable exposure parameter that can be used to describe the general working conditions and to guide the prevention and compensation of vibration-related health problems.

CRediT authorship contribution statement

Yi Sun: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Frank Bochmann:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Conceptualization. **Winfried Eckert:** Writing – review & editing, Project administration, Funding acquisition, Data curation. **Benjamin Ernst:** Writing – review & editing, Validation. **Christian Freitag:** Writing – review & editing, Project administration, Data curation. **Uwe Kaulbars:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Data curation. **Uwe Nigmann:** Writing – review & editing, Validation, Supervision, Data curation. **Christina Samel:** Writing – review & editing, Validation, Methodology. **Christian van den Berg:** Writing – review & editing, Validation, Supervision, Data curation. **Nastaran Raffler:** Writing – review & editing, Validation, Methodology, Data curation.

Conflicts of interest

We acknowledge that there is no financial interest or benefit arising from the application of this research project.

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