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Original Article

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Evaluation of hand–arm vibration (HAV) exposure among groundskeepers in the southeastern United States

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Abstract

Objective: The objectives of this study were to evaluate daily hand–arm vibration (HAV) exposure among groundskeepers, characterize power tools used, and estimate lifetime cumulative HAV exposure dose.

Methods: Seventeen groundskeepers and ten office workers employed at two US southeasterrn institutions were recruited as a target exposure group and a reference group, respectively. A 6-d exposure assessment of HAV was scheduled, and vibration dosimeters were used to obtain daily vibration exposure value, *A*(8). Information on power tools used and corresponding operation duration was recorded to assign the real-time vibration data collected from the dosimeters for tool characterization in terms of vibration total value (a_{hv}) and frequency. Lifetime cumulative exposure dose, $a_{hv\text{-lifetime}}$, was determined using a_{hv} for all tools used and lifetime exposure duration obtained through a questionnaire.

Results: The individual groundskeepers' average *A*(8) ranged from 0.8 to 2.6 and from 1.0 to 2.6 m/s^2 for the right hand and left hands, respectively. Among 11 power tools used by the groundskeepers, grass trimmers contributed the most to the vibration exposure. The average a_{hv} of the individual tools ranged from 8.0 (chainsaws) to 1.9 m/s^2 (seating mowers and handheld blowers) for the right hand and from 6.4 (push mowers) to 1.4 m/s^2 (backpack blowers) for the left hand. The highest acceleration peak of grass trimmers, edgers, backpack blowers, pole saws, riding blowers, and hedgers was observed between 100 and 200 Hz while riding mowers, seating mowers, push mowers, and chainsaws showed the highest acceleration peak at lower frequencies (≤63.5 Hz). The groundskeepers' average $a_{hv\text{-lifetime}}$ was 76,520.6 and 61,955.5 h m/s^2 for the right and left hands, respectively. The average $a_{hv\text{-lifetime}}$ of office workers was 2,306.2 and 2,205.8 h m/s^2 for the right and left hands, respectively, which was attributed to personal hobby activities.

Conclusion: Three groundskeepers' average *A*(8) reached 2.5 m/s^2, the Action Limit recommended by the American Conference of Governmental Industrial Hygienists (ACGIH). The highest contribution to the vibration exposure was observed during grass trimmer operations with a major acceleration peak at 100 Hz. The groundskeepers' $a_{hv\text{-lifetime}}$ was 33 and 28 times higher for the right and left hands, respectively, than the office workers.

Key words: exposure measurement; groundskeepers; hand–arm vibration; handheld power tools; hand-transmitted vibration; HAVS; segmental vibration.

What's Important About This Paper?

Power tool operators such as groundskeepers who use vibrating hand tools on a daily basis are at risk of hand–arm vibration syndrome. This was the first study in the US which conducted daily exposure assessment among groundskeepers in the field, during the use of a broad range of vibrating tool types. This study found 18% of groundskeepers exceeded the Action Limit recommended by the American Conference of Governmental Industrial Hygienists (ACGIH). Grass trimmers contributed the most to the vibration exposure dose with a major peak at 100 Hz, providing occupational health and safety (OHS) professionals with important information for the selection of appropriate control measures.

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Introduction

Workers whose hands and arms exposed to excessive vibration can experience vascular, neurological, and musculoskeletal disorders, collectively known as hand–arm vibration syndrome (HAVS) (Pelmear et al. 1993; Bovenzi 1998). In advanced stages, HAVS may become irreversible and lead to disability of upper extremities (House et al. 2009; Bodley et al. 2015; Zimmerman et al. 2020). It is estimated that approximately 2.5 million workers are exposed to hand–arm vibration (HAV) from power tools with a 20-50% prevalence of HAVS in the United States (Alvarez *et al.*, 2019). Studies have found that the magnitude and exposure duration of HAV are positively associated with the development of the vascular symptoms of HAVS (Bovenzi et al. 1994; Heaver et al. 2011).

Currently available HAV-related standards and guidelines, including American National Standard Institute (ANSI) S2.70–2006, American Conference of Governmental Industrial Hygienists (ACGIH) TLVs, and EU Directive 2002/44/EC, set the daily exposure limit value at 5 m/s^2 and the daily exposure action value at 2.5 m/s^2 for an 8-h work shift (European Parliament and the Council of the European Union 2002; American National Standards Institute 2006; American Conference of Governmental Industrial Hygienists 2018). Exposure assessment can provide the information on individual worker's daily HAV exposure based on the vibration magnitude and exposure duration. In addition, the identification and characterization of vibration sources through exposure assessment (e.g. magnitude, frequency, and cumulative exposure for each individual power tool) can facilitate proper selection of personal protective equipment (PPE) and engineering controls (Dong et al. 2021).

The latest estimate shows that in the United States, the number of groundskeepers who are at risk of HAVS due to the frequent use of vibrating equipment is over 1 million with an expected growth rate of 5% from 2021 to 2031 (Palmer et al. 2001; Bureau of Labor Statistics 2022). However, exposure assessment studies for groundskeepers are extremely limited, particularly in the United States (Oh 2022). One of the reasons for the limited number of studies on such outdoor power tool operators with high mobility would be the limitation of the conventional measuring instrument, the tool-attached accelerometer (Clemm et al. 2021). Traditionally, the accelerometers are attached to the vibration tool (e.g. handles) with a long electrical cable connected to a data analyzer, which makes it difficult to monitor outdoor workers who use a variety of power tools throughout their work shift. Recently, the vibration dosimeter, a personal vibration level meter which usually comes with an accelerometer-contained adapter which is worn on or held by the user's hand, is becoming popular due to the practicality, allowing real-time data collection for the workers' entire work shift in which multiple power tools are often used (Oliveira Júnior et al. 2019; Clemm et al. 2020, 2021; Dong et al. 2021).

There is inconsistency in the existing exposure assessment studies, which has limited the researchers in estimating lifetime HAV exposure to identify the individual groundskeepers vulnerable to HAVS. Risk assessment model related to HAVS is addressed in the International Organization for Standardization (ISO) 5349-1: Mechanical vibration—Measurement and evaluation of human exposure to hand-transmitted vibration—Part 1: General requirements, which was based on the number of years of exposure and the level of vibration intensity to predict the prevalence of secondary Raynaud's phenomenon, the best known vascular disorder of HAVS, in 10% of exposed population (International Organization for Standardization 2001a; Nilsson et al. 2017). Although the risk assessment model in ISO 5349-1 shows that lifetime HAV exposure duration and exposure level are the major factors in the prediction of HAVS, the method to estimate the lifetime HAV exposure duration and magnitude has not yet been standardized. More recently, a questionnaire from the risks of occupational vibration exposure (VIBRISK) project conducted in Europe has been used in estimating lifetime HAV exposure dose based on lifetime HAV exposure duration and magnitude (Griffin and Bovenzi 2007; Landsbergis et al. 2019; Clemm et al. 2020).

Therefore, the aims of the present study were to (1) evaluate the daily HAV exposure level among groundskeepers by employing vibration dosimeters, (2) characterize power tools and equipment used by groundskeepers, and (3) estimate the lifetime cumulative HAV exposure dose using questionnaires on exposure history adapted from the VIBRISK technical report.

Materials and methods

Study population and monitoring

IRB approval was obtained prior to the study (UAB IRB #300008388). Workers aged over 18 whose primary job involved power tool use in the ground maintenance industry were targeted as an exposure group, and 17 groundskeepers employed at two universities in Alabama were recruited. In addition, 10 office workers who had not been using vibrating tools on a regular basis were recruited from one of the institutions mentioned above as a reference group. Each study participant was scheduled to be monitored for 6 workdays to account for the daily variations of the vibration exposure. To take the monthly variations of HAV exposure levels into account, the first three monitoring (i.e. sampling) days were scheduled within a week at the beginning of the study, and the second three monitoring days were scheduled within a week approximately a month after the first sampling period. The study was conducted from April to December 2022 with the exposure group and from April to Sep 2023 with the control group. The researchers followed each study participant in the exposure group for the entire monitoring period and recorded the vibrating tools/equipment used and corresponding operation duration. Eleven types of power tools/equipment used by the participants during the monitoring period included grass trimmers, riding mowers, seating mowers, edgers, backpack blowers, push mowers, pole saws, hedgers, riding blowers, hand-held blowers, and chainsaws (Fig. 1). Table 1 shows the names of manufacturers and models of the tools observed in the study. The study participants in the reference group were asked to self-log their activities as well as the time when they took off the monitoring instrument such as for dining, using restroom, and breaks.

Sampling instrument and questionnaires

Tri-axial vibration dosimeters (SV103, Svantek SP. Z O. O., Warszawa, Poland) were used to evaluate daily HAV exposure levels, as shown in Fig. 1(a). The adapter of the dosimeter was worn on both palms of the participants and the meter unit connected to the adapter was attached to the participant's both arms using a Velcro arm strap. The pre- and post-calibrations were conducted at an acceleration of 10 m/s² and frequencies at 79.58 and 159.2 Hz using a vibration calibrator (SV110, Svantek SP. Z O. O., Warszawa, Poland).

The questionnaire adapted from the EU VIBRISK project was used to obtain the study participants' demographic characteristics and the personal vibration exposure history. Questions related to the study participant's demographic characteristics included age, biological sex, race, ethnicity, dominant hand, years of employment as groundskeeper or relevant occupation. Questions regarding the personal vibration exposure history included duration of current and past jobs, vibration tools used in each job and outside of work, weeks of using the vibrating tools per year, days of using the vibrating tools per week, and hours of using the vibrating tools per day.

Daily vibration exposure, *A*(8)

The ISO 5349-1 and ISO 5349-2 (International Organization for Standardization 2001a, 2001b) guidelines were followed for the HAV measurement and calculations. Frequency-weighted root-mean-square (r.m.s.) acceleration values for the three axes (a_{hwx}, a_{hwy}, and a_{hwz}) in m/s² and vibration total value (a_{hv}) in one second time resolution ($a_{hv}(t)$) were collected from the dosimeter for the entire work shift. One-third octave band analysis from 0.8 to 1,250 Hz center frequency was performed to characterize the vibration frequency of the individual vibration sources.

All data was downloaded using Supervisor software version 1.8.21 (Svantek SP. Z O. O., Warszawa, Poland). Daily vibration exposure, $A(8)$, was calculated based on the formula below to compare with the available exposure limit values.

$$A(8) = a_{\mathrm{hv}}\sqrt{\frac{T}{T_0}}, \quad (1)$$

where a_{hv} is the vibration total value, T is the daily exposure duration, and T_0 is the reference 8-hr exposure duration. The average $A(8)$ for the individual groundskeepers and for the groups was determined by calculating the arithmetic mean.

Daily HAV exposure dose for tool characterization

The real-time vibration data, ($a_{hv}(t)$), obtained from each groundskeeper was divided by each tool operation, and each participant's the tool-specific average vibration magnitude in a_{hv} was determined by calculating time-weighted r.m.s. values for the tool operation durations. If the participant operated a specific tool only one time throughout the monitoring period, the one-time measurement data was considered as an average. The tool-specific average vibration magnitude for all study participants was then determined by calculating the arithmetic mean by treating each study participant as one sample to characterize the vibration source.

Daily HAV exposure dose of each individual tool without 8-hr shift normalization was calculated by multiplying each participant's tool-specific average vibration magnitude by corresponding operation duration. Daily HAV exposure dose of all tools used was obtained by summation as follows:

$$\text{DailyHAV exposure dose}_j \left(\text{hours}\cdot \text{m/s}^2 \cdot \text{day}^{-1}\right) = \sum_{i=1}^{n} \text{hours working per day}_{ij} \times \text{average } a_{hv-ij} \quad (2)$$

where i and j are the ith type of vibration tools used by the jth study participant, respectively.

The average daily HAV exposure dose for the individual groundskeepers and the exposure group was determined by calculating the arithmetic mean.

Lifetime cumulative HAV exposure dose

The lifetime cumulative HAV exposure dose ($a_{\text{hv-lifetime}}$) for each individual was estimated by multiplying the exposure duration for each tool determined based on the lifetime exposure history from the questionnaire

Fig. 1. Study participants wearing (a) vibration dosimeters during the operation of: b) grass trimmer, c) riding mower, d) seating mower, e) edger, f) backpack blower, g) push mower, h) pole saw, i) hedger, j) riding blower, k) hand-held blower, and l) chainsaw.

Table 1. Manufacturer, model, and manufacture-reported vibration level of the power tools observed in the study.

Tool	Brand	Model	Right handle/Left handle vibration level in m/s^2
Grass trimmer	Stihl	FS 111R, FS 91R, FS 94R, FS 111 RX[b]	5.0-6.1[a] / 5.1-6.6[a]
Backpack blower	Stihl	BR800C, BR600	1.8 to 3.5[a]/NA
	Redmax	EZB8550	NA
	Husqvarna	580BTS, 360BT	1.6 to 2.5[c]/NA
Edger	Stihl	FC 96	NA
Riding mower	SCAG	SVRII-36A-19FX	NA
Pushing mower	Honda	HRC216	NA
	Toro	21″ commercial heavy-duty	NA
Seating mower	Exmark	Lazer Z x series	NA
	Toro	Z master commercial	NA
	SCAG	STTII-61V-31DFI	NA
	Walker	T27i	NA
Hedger	Stihl	HS 82R, HS 82T, HS 56	2.1 to 5.5[a]/2.4 to 4.7[a]
	Husqvarna	322HD60	4.3[c]/4.4[c]
Pole saw	Stihl	HTA 135, HL 94	NA
Chainsaw	Greenworks	40V-CSF403	NA
	Husqvarna	455 Rancher	6.9[c]/3.8[c]
Handheld blower	Ryobi	18V	NA
Riding blower	Hurricane power	Z3	NA

[a]Vibration values reported for the same models sold in Europe (Andreas Stihl 2024a, 2024b, 2024c, 2024d, 2024e, 2024f).
[b]Vibration value unavailable for the model FS 111 RX.
[c]Vibration value reported from Husqvarna (Husqvarna 2024a, 2024b, 2024c).

and the tool specific a_{hv}, and $a_{hv\text{-lifetime}}$ of all tools combined was determined by summation as follows:

$$a_{\text{hv-lifetime}-j}(\text{hours}\cdot \text{m/s}^2) = \sum_{i=1}^{n} [(\text{hours per day}_{ij} \times \text{days per week}_{ij} \times \text{week per year}_{ij} \times \text{year}_{ij}) \times \text{average } a_{hv-ij}] \quad (3)$$

where i is the ith type of vibration tools used by the individual, j is the jth study participants, and n is the total number of types of vibration tools used by the jth study participant in his life (Griffin and Bovenzi 2007; Clemm et al. 2020). The mean $a_{hv\text{-}i}$ of the exposure group substituted for $a_{hv\text{-}ij}$ when the jth participant did not operate the ith tool during the monitoring period. The average $a_{hv\text{-lifetime}}$ for each group was then determined by calculating the arithmetic mean. Due to the potential recall bias on exposure durations, a correction factor ($C_{\text{hours per day}}$) was calculated based on the observations made on the daily operation durations of each tool for each participant as follows and applied when the hours per day is not zero in the Equation (2) above, as shown in Equation (4):

$$C_{\text{hours per day}-ij} = \frac{\text{hours per day}_{ij-\text{recorded by dosimeters}}}{\text{hours per day}_{ij-\text{questionnaire}}} \quad (4)$$

where i and j are the ith type of vibration tools used by the jth study participant, respectively.

Data analysis

The descriptive statistics were conducted in the R software Version 4.3.0 (R foundation, Vienna, Austria). First, the average and range of the study participants' demographic characteristics and $A(8)$ were calculated. Second, the average, error, and range of vibration magnitude (a_{hv}) in r.m.s. were computed. The error of a_{hv} was used instead of standard deviation because the average a_{hv} was obtained by calculating time-weighted r.m.s. values (i.e. error of r.m.s.) as shown in Equation (5):

$$\text{Error of vibration magnitude } (a_{hv}) \text{ in r.m.s.} = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n}} \quad (5)$$

where n is the number of samples for each tool, x is the ith vibration magnitude and $\bar{x}$ is the average of time-weighted r.m.s. values of the n samples. In addition to the exposure and reference groups, workers whose average $A(8)$ reached 2.5 m/s^2 was also examined independently during the analysis of the daily HAV exposure dose and lifetime exposure dose. a_{hv} higher than

50 m/s² was considered abnormal and excluded from data analysis.

Results

Study participants' demographic characteristics

Table 2 shows the study participants' demographic characteristics. All of the study participants' biological sex was male. The average age of the exposure group was 44 yr old (range 23 to 67) with the average years of working with vibration tools was 13 yr (range 1 to 27). The average age of the reference group was 43 yr old (range 22 to 73) with all the participants having zero year of experience in industries where regular use of vibrating tools was involved.

Daily vibration exposure, *A*(8)

Among the six monitoring days scheduled, 3 to 6 d of complete monitoring data were obtained from the exposure group, except for two study participants: one participant for 2 d and the other participant for 1 d (Supplementary Table S1). In the reference group, all 6 d of complete monitoring data were obtained from all participants, except for two participants whose data were available for 5 d. The data lost was caused by unexpected damage of the hand adapters of the vibration dosimeters. After excluding a_{hv} higher than 50 m/s², the ratio of a_{hv} excluded data from the total a_{hv} data for each participant per day was from 0% to 2.49%, with an average of 0.03%.

Supplementary Table S2 provides details on the average, standard deviation, and range of *A*(8) of the 17 individual groundskeepers and Table 3 summarizes the average *A*(8) and the average daily exposure duration. In the entire exposure group, the average *A*(8) ranged from 0.8 to 2.6 and from 1.0 to 2.6 m/s² for the right hand and left hand, respectively, with an average of 1.9 and 1.7 m/s² for right hand and left hand, respectively; the daily average exposure time was 3.8 h for both hands. The top three study participants in the exposure group whose average *A*(8) reached 2.5 m/s² in either hand had an average *A*(8) range of 2.5 to 2.6 and 2.0 to 2.6 m/s² for the right hand and left hand, respectively; the average daily exposure time was 4.1 h for both hands. The participants in the reference group did not use any vibrating tools during the sampling period while the daily a_{hv} of the office workers recorded by the dosimeters ranged from 0.4 to 1.5 and from 0.4 to 1.2 m/s² for right hand and left hand, respectively, mainly caused by typing and other activities in their office. *A*(8) of the reference group was not further calculated.

Table 2. Demographic characteristics of 27 participants

	Exposure group	Reference group
Number of participants (African American/Caucasian/Hispanic)	17 (4/7/6)	10 (2/5/3)
Biological sex (male/female)	17/0	10/0
Dominant hand (right/left)	15/2	10/0
Participant age in years (range)	44 (23 to 67)	43 (22 to 73)
Years of working in industries where involved the regular use of vibrating equipment (range)	12.8 (1 to 27)	0 (0 to 0)

Characterization of power tools

Details on average, error, and range of vibration total value (a_{hv}) in r.m.s. and the number of tool operation by each groundskeeper are presented in Supplementary Table S1, and the average daily HAV exposure dose along with exposure duration and magnitude for each power tool of the 17 individual groundskeepers in the exposure group are available in Supplementary Table S3. The average vibration magnitude (right hand a_{hv}/left hand a_{hv}) obtained from the groundskeepers who used those tools was 5.1/5.0, 4.1/4.1, 1.9/2.3, 6.1/6.0, 2.4/1.4, 6.5/6.4, 5.2/3.8, 4.1/3.1, 2.7/2.6, 1.9/1.7, and

Table 3. Average daily vibration exposure, *A*(8), and average daily vibration exposure duration among exposure group.

	Mean ± SD (range)		
	Duration of daily vibration exposure (h)	*A*(8) (m/s²)	
		Right hand	Left hand
Exposure group			
Total (*N*=17)	3.8 ± 1.1 (2.3 to 6.2)	1.9 ± 0.5 (0.8 to 2.6)	1.7 ± 0.5 (1.0 to 2.6)
Daily exposure ≥ 2.5 m/s² (*N* = 3)	4.1 ± 0.4 (3.6 to 4.5)	2.5 ± 0.04 (2.5 to 2.6)	2.3 ± 0.2 (2.0 to 2.6)

8.0/3.4 m/s² for grass trimmers, riding mowers, seating mowers, edgers, backpack blowers, push mowers, pole saws, hedgers, riding blowers, hand-held blowers, and chainsaws, respectively.

Figure 2 shows the percent contribution of the average daily HAV exposure dose by each tool to the average daily HAV exposure dose of all tools combined. Among the entire exposure group, the operation of grass trimmers resulted in the highest average daily HAV exposure dose (22.0%) on the right hand, followed by riding mowers (18.2%), seating mowers (14.6%), edgers (13.1%), backpack blowers (9.0%), pushing mowers (9.0%), pole saws (5.0%), hedgers (4.7%), riding blowers (3.7%), hand-held blowers (0.6%), and chainsaws (0.1%); on the left hand, the grass trimmers had the highest contribution (22.3%), followed by riding mowers (19.2%), seating mowers (18.4%), edgers (12.8%), push mowers (9.2%), hedgers (4.8%), backpack blowers (4.7%), pole saws (4.3%), riding blowers (3.7%), handheld blowers (0.6%), and chainsaws (<0.1%).

Among the three study participants whose average A(8) reached 2.5 m/s², push mowers had the highest percent contribution to the average daily HAV

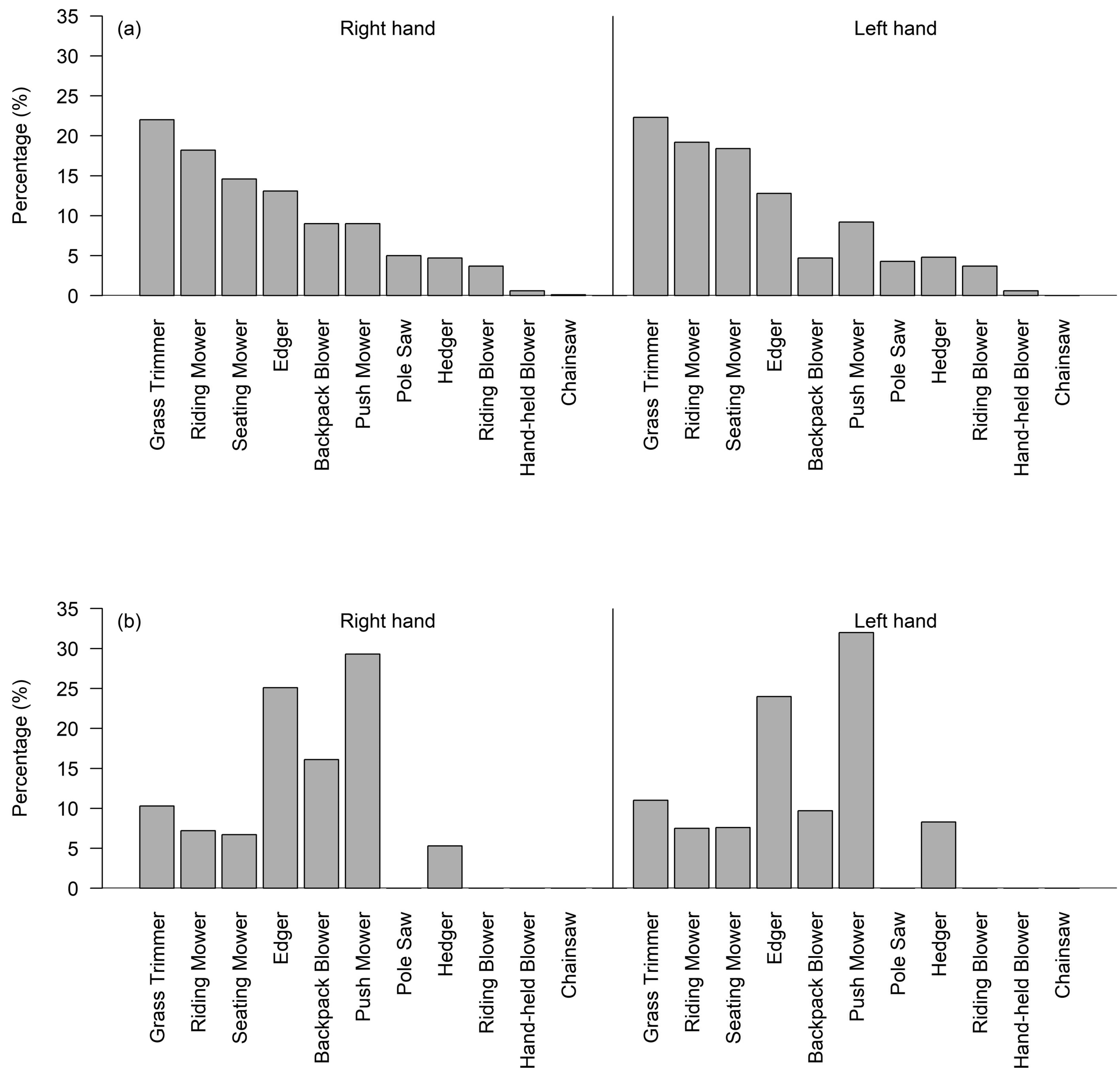

Fig. 2. Percent contribution of 11 vibrating tools to the average daily HAV exposure dose among: a) the entire exposure group and b) the three participants whose daily exposure reached 2.5 m/s² in the exposure group.

exposure dose on the right hand (29.3%), followed by edgers (25.1%), backpack blowers (16.1%), grass trimmers (10.3%), riding mowers (7.2%), seating mowers (6.7%), and hedgers (5.3%); on the left hand, the push mowers had the highest contribution (32.0%), followed by edgers (24.0%), grass trimmer (11.0%), backpack blowers (9.7%), hedgers (8.3%), seating mowers (7.6%), and riding mowers (7.5%).

Figure 3 shows the one-third octave band analysis for each vibrating tool obtained from the exposure group. The grass trimmer operation had major acceleration peaks at 100 Hz in the *x*-and *y*-axes on the right hand and 100 Hz in the all-axes on the left hand. The riding mower operation had the highest peak at 10 Hz in the *y*-axis for both right and left hands. The seating mower operation had two small peaks at 40 and 63.5 Hz in the *x*-axis and *y*-axis, respectively, for both hands. The edger operation had multiple peaks from 12.5 to 630 Hz with the highest peak at 160 Hz in the *x*-axis and 80 Hz in the *y*-axis for the right and left hands, respectively. The backpack blower operation had no obvious patterns with one small acceleration peak appeared at 125 Hz in the *y*-axis on the right hand. Multiple peaks were observed from the push mower operation with the highest peak at 50 Hz in the *y*-axis for both hands. The pole saw operation also had multiple peaks between 12.5 and 500 Hz with the highest peak at 160 Hz in the *z*-axis and 160 Hz in the *y*-axis for the right and left hands, respectively. The hedger operation had the highest peak at 160 Hz in the *y*-axis for both hands. The riding blower operation had smaller peaks with a major peak at 200 Hz in the *y*-axis for both hands. The hand-held blower operation had no obvious acceleration peaks similar to the backpack blowers. The chainsaw operation had multiple larger acceleration peaks between 5 and 35 Hz in the *x*-axis on the right hand while two major peaks appeared at 12.5 and 78 Hz in the *y*-axis and *x*-axis, respectively, on the left hand.

Estimation of lifetime cumulative HAV exposure dose

Individual data on $a_{hv\text{-}lifetime}$ for each tool, corresponding operation duration, and magnitude as well as correction factor are available in the Supplementary Materials (Tables S4 and S5). The 17 groundskeepers' $a_{hv\text{-}lifetime}$ ranged from 1,459.5 to 154,234.9 and from 1,253.1 to 140,702.6 h m/s^2 for the right and left hands, respectively, while the 10 office workers' $a_{hv\text{-}lifetime}$ ranged from 0 to 15,408.9 and from 0 to 15,217.2 h m/s^2 for the right and left hands, respectively. Table 4 shows the average lifetime exposure duration and the average $a_{hv\text{-}lifetime}$ estimated for each power tool among the entire exposure group, three study participants whose *A*(8) reached 2.5 m/s^2 in the exposure group, and the reference group. The average lifetime exposure duration for each tool of the entire exposure group was estimated to be from 0.2 h (handheld blowers) to 5,740.5 h (backpack blowers). Among the reference group, only four type of tools including grass trimmers, push mowers, handheld blowers, and chainsaws were reported in the questionnaire, and the estimated average lifetime exposure duration was from 15.0 h (chainsaws) to 279.2 h (push mowers). The groundskeepers' average $a_{hv\text{-}lifetime}$ was estimated to be 76,520.6 and 61,955.5 h m/s^2 for the right and left hands, respectively. Office workers' lifetime vibration exposure was attributed to personal lifestyle related activities, and the estimated average $a_{hv\text{-}lifetime}$ was 2,306.2 and 2,205.8 h m/s^2 for the right and left hands, respectively.

Among the entire exposure group, grass trimmers (22,750.8 h m/s^2) contributed the most to the average $a_{hv\text{-}lifetime}$ on the right hand, followed by backpack blowers (13,676.9 h m/s^2), chainsaws (13,476.4 h m/s^2), push mowers (9,277.3 h m/s^2), edgers (4,509.1 h m/s^2), seating mowers (4,030.2 h m/s^2), hedgers (3,161.0 h m/s^2), riding mowers (2,706.2 h m/s^2), pole saws (2,077.8 h m/s^2), riding blowers (854.5 h m/s^2), and handheld blowers (0.3 h m/s^2); on the left hand, grass trimmers (22,375.3 h m/s^2) had the highest contribution to the $a_{hv\text{-}lifetime}$ estimate, followed by push mowers (9,167.6 h m/s^2), backpack blowers (7,469.5 h m/s^2), chainsaws (5,744.3 h m/s^2), seating mowers (5,293.4 h m/s^2), edgers (4,447.2 h m/s^2), riding mowers (2,761.3 h m/s^2), hedgers (2,336.6 h m/s^2), pole saws (1,509.4 h m/s^2), riding blowers (850.7 h m/s^2), and handheld blowers (0.3 h m/s^2). Among the three study participants whose *A*(8) reached 2.5 m/s^2, chainsaws (2,594.0 h m/s^2) contributed the most to the average $a_{hv\text{-}lifetime}$ on the right hand, followed by grass trimmers (2,505.1 h m/s^2), push mowers (1,743.9 h m/s^2), and edgers (1,567.4 h m/s^2); on the left hand, grass trimmers (2,363.6 h m/s^2) contributed the most to the average $a_{hv\text{-}lifetime}$, followed by push mowers (1,747.8 h m/s^2), edgers (1,349.3 h m/s^2), and chainsaws (1,105.7 h m/s^2). Pole saws, riding blowers, and handheld blowers were not identified from the questionnaire of the three participants and these tools were not used during the monitoring period as well. Among the reference group, the push mowers (1,814.8 and 1,792.5 h m/s^2 for right hand and left hand, respectively) contributed the most to the $a_{hv\text{-}lifetime}$, followed by grass trimmers (330.8 and 326.3 h m/s^2 for right hand and left hand, respectively), chainsaws (120.0 and 51.2 h m/s^2 for right hand and left hands, respectively), and handheld blowers (40.6 and 36.0 h m/s^2 for right hand and left hand, respectively).

Discussion

The race/ethnicity of this study population was fairly evenly distributed both in the exposure group and

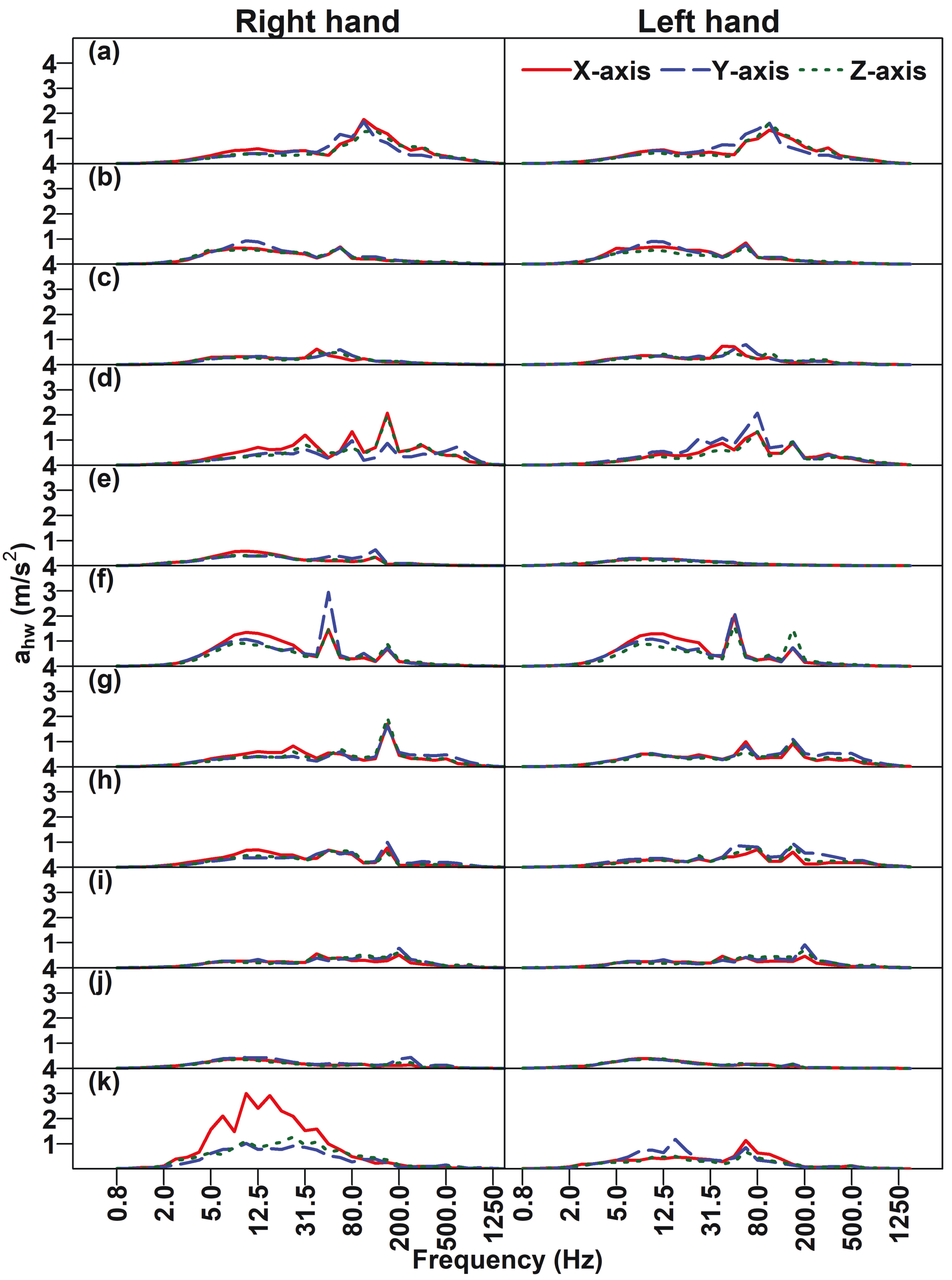

Fig. 3. W_h weighted frequency spectrum for the operation of: a) grass trimmers, b) riding mowers, c) seating mowers, d) edgers, e) backpack blowers, f) push mowers, g) pole saws, h) hedgers, i) riding blowers, j) hand-held blowers, and k) chainsaws. W_h: frequency weighting according to the ISO 5349-1.

Table 4. Average $a_{hv\text{-}lifetime}$ along with average exposure duration for each power tool of the entire exposure group, the three participants whose daily exposure was higher than 2.5 m/s^2 in the exposure group, and the reference group.

	Grass trimmer	Riding mower	Seating mower	Edger	Backpack blower	Push mower	Pole saw	Hedger	Riding blower	Handheld blower	Chainsaw	Total
Exposure group												
Total (N = 17)												
Average duration (h)	4,475.0	761.6	2,538.6	771.4	5,740.5	1,437.0	400.4	767.0	278.7	0.2	1,684.5	18,854.9
Average $a_{hv\text{-}lifetime}$ (h m/s^2)												
Right hand	22,750.8	2,706.2	4,030.2	4,509.1	13,676.9	9,277.3	2,077.80	3,161.0	854.5	0.3	13,476.4	76,520.6
Left hand	22,375.3	2,761.3	5,293.4	4,447.2	7,469.5	9,167.6	1,509.4	2,336.6	850.7	0.3	5,744.3	61,955.5
Daily exposure ≥ 2.5m/s2 (N=3)												
Average duration (h)	534.6	98.2	240.1	281.1	251.3	323.5	0.0	1.5	0.0	0.0	324.3	2,054.6
Average $a_{hv\text{-}lifetime}$ (h·m/s^2)												
Right hand	2,505.1	436.5	525.9	1,567.4	657.1	1,743.9	0.0	3.3	0.0	0.0	2,594.0	10,033.3
Left hand	2,363.6	427.7	536.1	1,349.3	299.3	1,747.8	0.0	3.4	0.0	0.0	1,105.7	7,832.8
Reference group (*N* = 10)												
Average duration (h)	65.3	0	0	0	0	279.2	0	0	0	20.8	15.0	380.3
Average $a_{hv\text{-}lifetime}$ (h m/s^2)												
Right hand	330.8	0.0	0.0	0.0	0.0	1,814.8	0.0	0.0	0.0	40.6	120.0	2,306.2
Left hand	326.3	0.0	0.0	0.0	0.0	1,792.5	0.0	0.0	0.0	36.0	51.2	2,205.8

the reference group. While there was no restriction among exposure group study participants' biological sex during the recruitment, all the study participants' biological sex was males, reflecting the male-dominated grounds maintenance industry (Bureau of Labor Statistics 2023). The study participants' age in the exposure group was comparable with the reference group. Among the 17 groundskeepers in the exposure group, the average years working with vibration tools was 12.8 yr with a range from 1 to 27 yr, showing the study covered both junior and senior groundskeepers.

Three study participants' average $A(8)$ on either hand reached the action limit of 2.5 m/s^2, recommended by the ACGIH: two groundskeepers on both hands and one groundkeeper on the right hand. If the study participants continue to work in the same pattern of vibrating tool use as they did on our monitoring days, the implementation of appropriate control measures would be recommended. For example, vibrating tools with anti-vibration handles or anti-vibration gloves can be utilized. Also, training to advise the workers to grab the tool handle as lightly as possible can help lower vibration exposure through the reduction of coupling force. The three study participants' average $A(8)$ was 1.3 times and 1.4 times higher than the entire exposure group for the right hand and left hand, respectively. The difference of daily operation duration of vibrating tools between the three study participants and the entire exposure group was 0.3 h, indicating a greater contribution of a_{hv} to the difference in $A(8)$. Compared with other studies which used the identical vibration dosimeters, this present study showed lower average $A(8)$ (; Oh 2022). In Oh's study, HAV exposure among two groundskeepers who used grass trimmers and backpack blowers was measured, and the average $A(8)$ was 3.3 and 3.5m/s^2 for right hand and left hand, respectively (Oh 2022). In the Oliveira et al.'s study, the average $A(8)$ measured among brush cutter operators were 4.5 and 5.0 m/s^2 for right hand and left hand, respectively (Oliveira Júnior et al. 2019). The use of power tools with relatively lower vibration magnitude in the present study would be one of the reasons for the lower daily vibration exposure.

The information on the tool vibration magnitude of most power tools used in the study conducted in the US is unavailable as shown in Table 1. Husqvarna was the only manufacturer which provides vibration values of the tools observed in the present study. Stihl had vibration data available for the same models but they are sold in Europe while it can be assumed that the vibration magnitude of the same models sold in Europe and in the US will be comparable because of the same specifications. The comparison of the vibration exposure data measured in this study with the manufacture-reported values may not be appropriate. The main reason is that the average vibration magnitude determined in this study for each type of tools was calculated by combining different tool models from different manufacturers if there was more than one model used in each tool category; several manufacturers/models of the same type of tool such as grass trimmer, backpack blower, hedger, and chainsaw were often used several times in one work shift (Table 1). Nonetheless, there may be a pattern: the vibration exposure values measured on the user's hand in our study tended to be lower than the manufacturer-reported tool vibration data primarily due to the reduction in energy during vibration transmission. The average vibration exposure values of the backpack blower, hedger, and chainsaw from Husqvarna measured in this study were 0.1 to 1.3 m/s^2 lower than the highest tool vibration values reported from the manufacturer except the right-hand chainsaw data which was 1.1 m/s^2 higher than the manufacturer-reported right handle value. The higher vibration value measured from the chainsaw was more likely due to the limited number of repeated measurements. Three types of power tools from Stihl including the grass trimmer, backpack blower, and hedger (Andreas Stihl 2024a, 2024b, 2024c, 2024d, 2024e, 2024f; Husqvarna 2024a, 2024b, 2024c) also showed 1.0 to 2.4 m/s^2 lower vibration measurement values than the highest tool vibration magnitude provided by the manufacturer.

The vibration magnitude analyzed by tool type showed between- and within-subject variations as reported in the literature. In the Oh et al.'s study, the average vibration value measured on both hands of two participants during grass trimmer (STIHL FS 91R) operation ranged from 4.5 to 7.2 m/s^2, and in the present study it was from 3.8 to 7.0 m/s^2 (Oh 2022). Bernardi et al. reported the average acceleration ± standard deviation of 4. 4 ± 1.0 m/s^2 among six operators during the operation of the bike-handle brush cutter with a mowing head (Bernardi et al. 2018). The Oh et al.'s study also reported the average right-hand vibration magnitude during backpack blower operation to be 1.2 and 2.3 m/s^2, and the present study observed 1.9 to 2.7 m/s^2 (Oh 2022). Such variations between participants can be caused by the differences in cutting object, working technique, and coupling force (Mallick 2008, 2010; Rottensteiner et al. 2012; Lindenmann et al. 2021). A relatively high within-subject variation in vibration magnitude was observed during edger, grass trimmer, riding mower, and backpack blower operations in our study. As reported in Table S1, participant AB (i.e. subjectID) in particular showed an abnormally high difference between the lowest exposure (2.9 m/s^2) and the highest exposure (10.9 m/s^2) during six times of edger operation. Participant AH had the next highest acceleration difference between the lowest (3.8 m/s²) and the highest (8.7 m/s²) on the left hand during 16 times of grass trimmer operation. In a Rottensteiner et al.'s study, one operator cut different types of wood using three different chainsaw models and showed an acceleration range of 2.8 to 8.4 m/s² on either hand (Rottensteiner et al. 2012). The variations within participants can be attributed to tool design/condition and cutting object as well as individual factors such as working skills (Rottensteiner et al. 2012; Landekić et al. 2020; Lindenmann et al. 2021).

Among the 11 powered tools used, the operation of the grass trimmers substantially contributed to the average daily HAV exposure dose in the exposure group (22.0% for right hand and 22.3% for left hand). The operation of grass trimmers, riding mowers, and the seating mowers accounted for more than 50% of the exposure dose among the exposure group, while the operation of edgers and push mowers contributed to more than half of the exposure dose among the three study participants whose $A(8)$ reached 2.5 m/s².

Studies showed that exposure to higher vibration frequency (≥100 Hz) could result in higher impacts in the finger and hand region, while lower frequency vibration (i.e. ≤25 Hz) is predominantly perceived in the arms and shoulder (Welcome et al. 2015; Singh et al. 2020; Dong et al. 2021). The operation of grass trimmers, edgers, pole saws, hedgers, and riding blowers which major peaks appeared in the range between 100 and 200 Hz may suggest higher impact in the operator's fingers and hands, on the other hand, the major peaks of operating riding mowers and chainsaws occurred below 25 Hz, which may imply more shoulder and arm disorders. Among the three study participants whose $A(8)$ reached 2.5 m/s², push mowers and edgers which were top two tools contributed the most to the daily vibration exposure dose for both hands, showed wide frequency spectrum, indicating the need for protection in the broader upper extremity regions. However, it should be note that there is still limited knowledge on the transmission of vibration energy which is also contributed by other factors such as vibration magnitude and direction (Dong et al. 2021).

The major frequency peak during the grass trimmer operations identified in the study was lower than the literature (Bernardi et al. 2018; Oliveira Júnior et al. 2019; Oh 2022). Oh observed two major peaks at 125 to 200 Hz and 300 to 630 Hz during grass trimmer operations (Oh 2022). This is more likely due to the different tool models used. Oliveira Junior et al. and Bernardi et al. observed a major frequency peak at 160 Hz from a loop-handle brush cutter and a bike-handle brush cutter, respectively (Bernardi et al. 2018; Oliveira Júnior et al. 2019). The difference would be mainly because of the different structures between brush cutters and grass trimmers. In our previous study, we found that the attenuation effects of general purpose gloves on HAV was notable at frequency higher than 200 Hz (Oh et al. 2023). The present study did not restrict wearing gloves and the adapters were worn inside gloves to capture the true exposure of the workers. Twelve out of the 17 participants in the exposure group occasionally wore gloves during the monitoring period which may be one of the reasons for observing the dominant frequency at lower ranges.

The chainsaw operations in the present study showed the highest acceleration peak at 10 and 160 Hz for right hand and left hand, respectively. The 160 Hz peak for the left hand was also observed in a Rottensteiner et al.'s study (Rottensteiner et al. 2012) while the peak at 10 Hz for right hand was not observed in the study. Different tool models and tool ages/conditions may be one of the possible reasons (Landekić et al. 2020). In addition, the different measuring instruments used (i.e. tool-attached accelerometers vs. vibration dosimeters) may have affected the HAV measurement results (Clemm et al. 2021).

The backpack blowers showed a major peak at 125 Hz which was similar to the results from the Oh's study, although the exactly same models were not used (Oh 2022). Calvo et al. showed two major peaks at 100 and 200 Hz during the operation of an agricultural mist blower which structure was quite different than the backpack blowers examined in our study (Calvo et al. 2019). HAV data on riding mower, edger, seating mower, push mower, pole saw, riding blower, hedger, and handheld blower are extremely limited in the current literature.

The average lifetime exposure dose of the exposure group was 33.2 times higher on the right hand and 28.1 times higher on the left hand than the reference group. Clemm et al. showed that the average lifetime exposure dose for the operation of rock drills and impact wrenches were 13,219 and 2,209 h m/s², respectively (Clemm et al. 2020). The operation of grass trimmer among our exposure group was over 1.6 times higher than professional rock drill operators. However, the comparison between different power tools and equipment should be careful due to the differences in tool characteristics.

There were limitations of the study. First, this study used vibration dosimeters to measure the HAV level, which may underestimate the fingers HAV exposure dose if the user's fingers make more contact with the tool handle than their palms (Clemm et al. 2021). However, all of the 11 power tools used in the study have triggers at the handle, requiring users a tight grip with their palms to operate the tools (Clemm et al. 2020). Second, the monitoring was conducted for up to six sampling days per each individual groundskeeper, which did not allow us to capture the operations of all the powered tools used by each participant. The chainsaw substantially contributed to the overall lifetime exposure while the operation of chainsaw was only captured from one study participant. The determination of the average vibration magnitude for chainsaws based on the limited number of operations may not represent the true exposure of the workers, lowering the internal validity of the data. Also, the relatively large within-subject variation observed from certain tools among several participants may lower the internal validity of the data while the number of repeated measurements did not seem to directly affect the variations within subjects. More thorough observations on the subject whose variation is abnormally high are needed to obtain more reliable exposure assessment results. Third, the recall bias from the survey may have affected the estimation of lifetime HAV exposure dose, especially from those tools intermittently used (Palmer et al. 2000). While the correction factor was applied, the systemic error may still be present. Lastly, the variations in vibration magnitude between study participants may limit the application of the study results to other occupational groups in risk assessment though such variations are commonly observed in the current literature. The HAV results obtained from one occupation with the small sample size limit the external validity. More studies are necessary to obtain results which are more replicable and generalizable.

Conclusion

Three groundskeepers' average $A(8)$ among seventeen groundskeepers exceeded the ACGIH AL. The highest contribution to vibration exposure dose was observed during the operation of grass trimmers with a major peak at 100 Hz, providing the occupational health and safety professionals with valuable information on the selection of proper PPE and implementation of engineering controls. The lifetime exposure dose of the groundskeepers was estimated to be over 28 times higher than the office workers, and the lifetime dose estimated based on the actual monitoring results will be useful to examine the exposure–response relationship for future risk assessment. More investigations are necessary on the groundskeepers' vibration exposure to help obtain more replicable and generalizable data.

Conflict of interest

The authors declare no conflict of interest in relation to the material presented in this Article.

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Data availability

The data underlying this article cannot be shared publicly due to the privacy of individuals that participated in the study. De-identified data can be shared on reasonable request to the corresponding author.

Supplementary material

Supplementary material is available at *Annals of Work Exposures and Health* online.

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